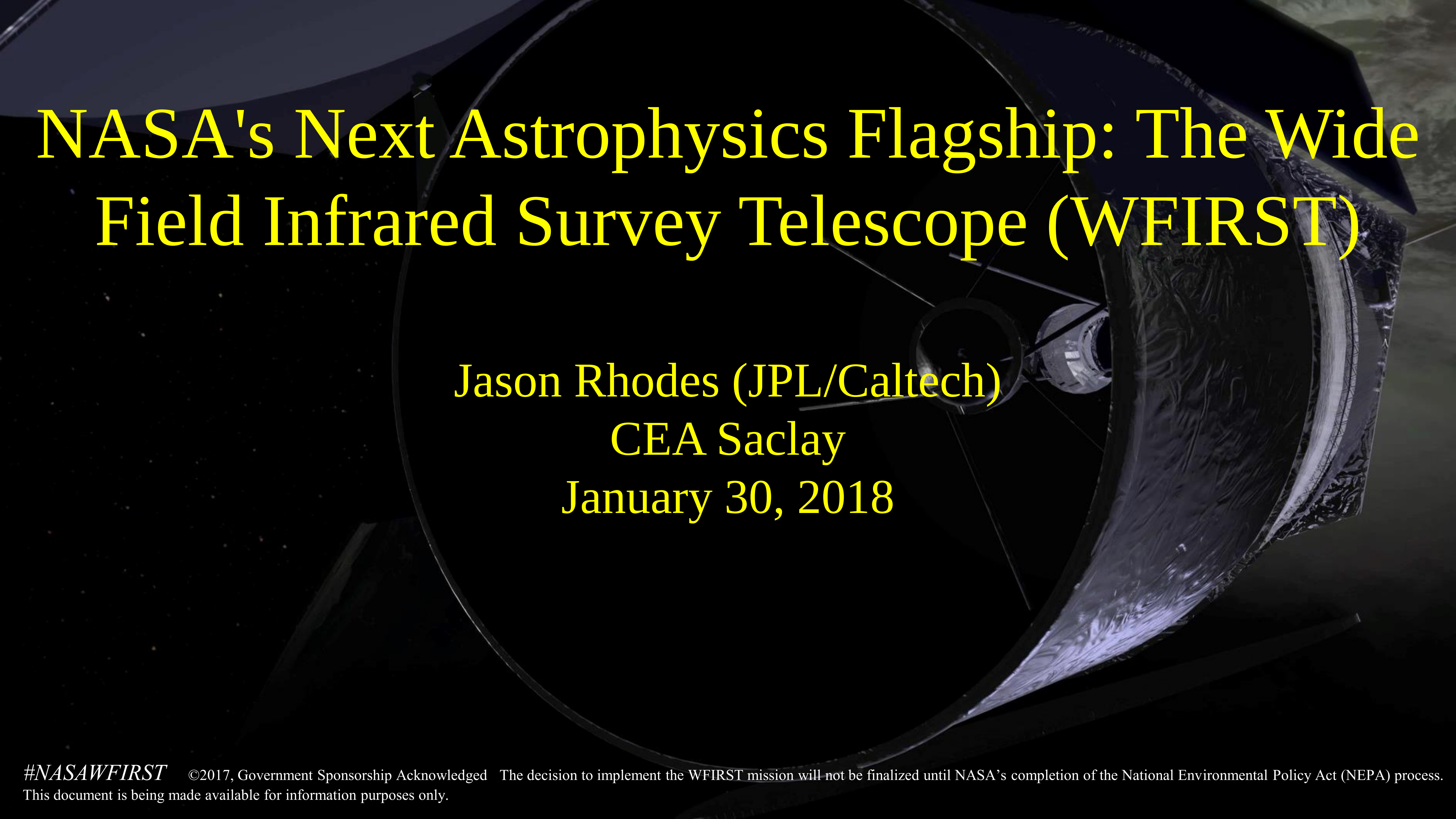


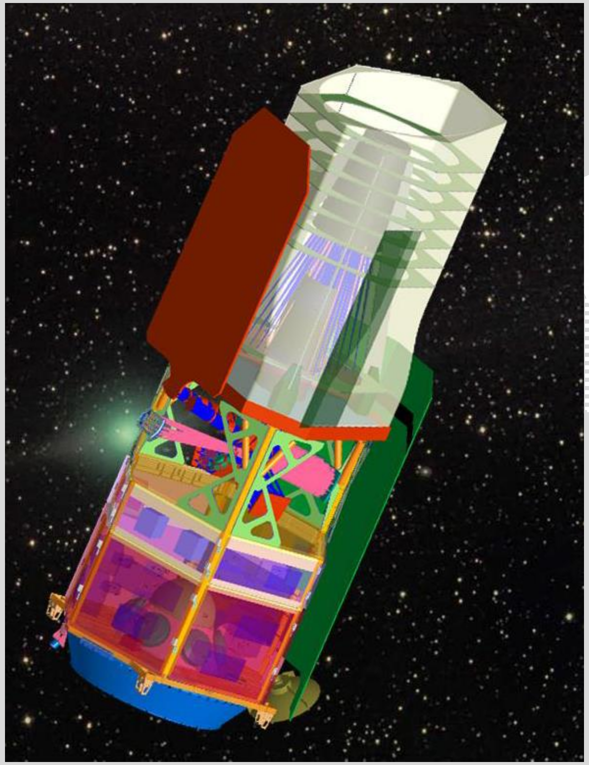
NASA's Next Astrophysics Flagship: The Wide Field Infrared Survey Telescope (WFIRST)

Jason Rhodes (JPL/Caltech)

CEA Saclay

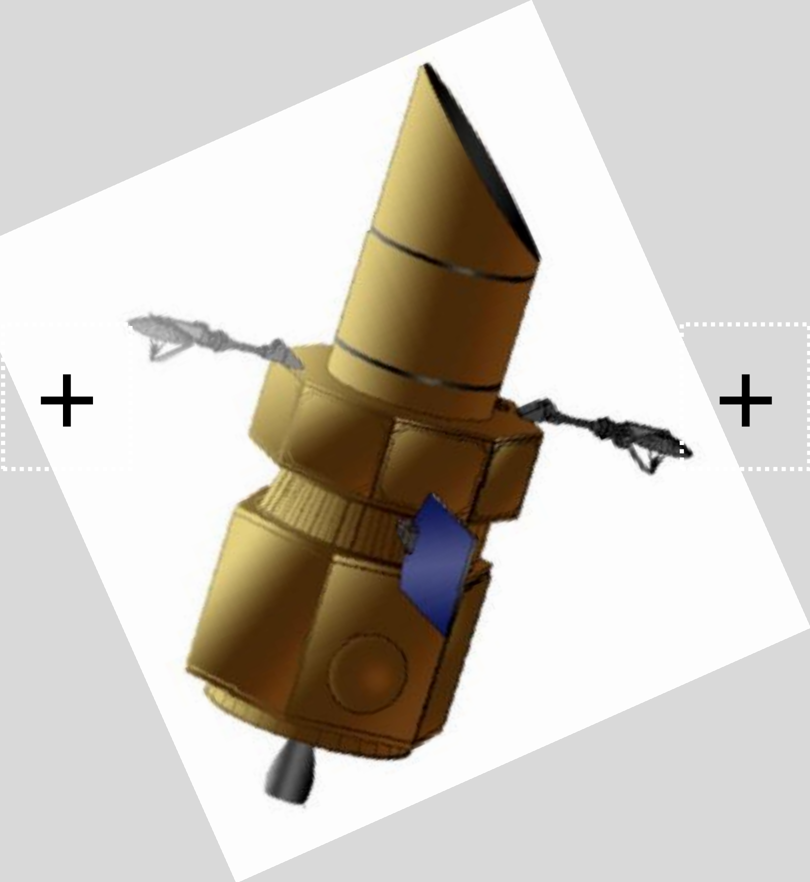
January 30, 2018

WFIRST =



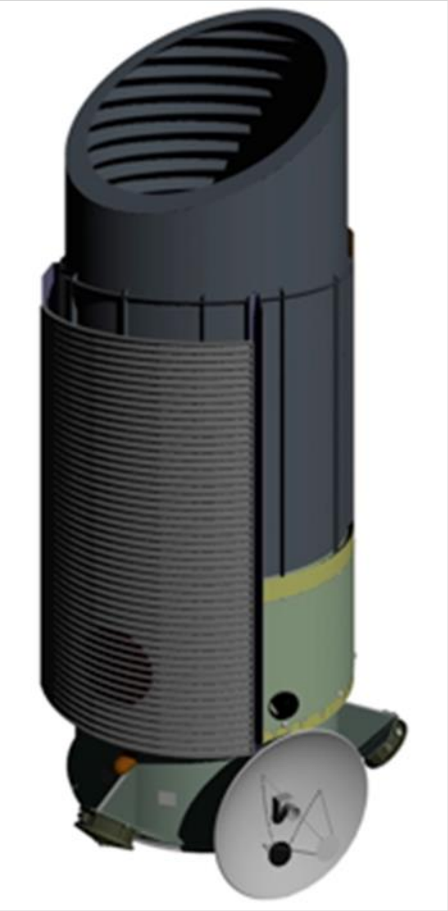
JDEM

+



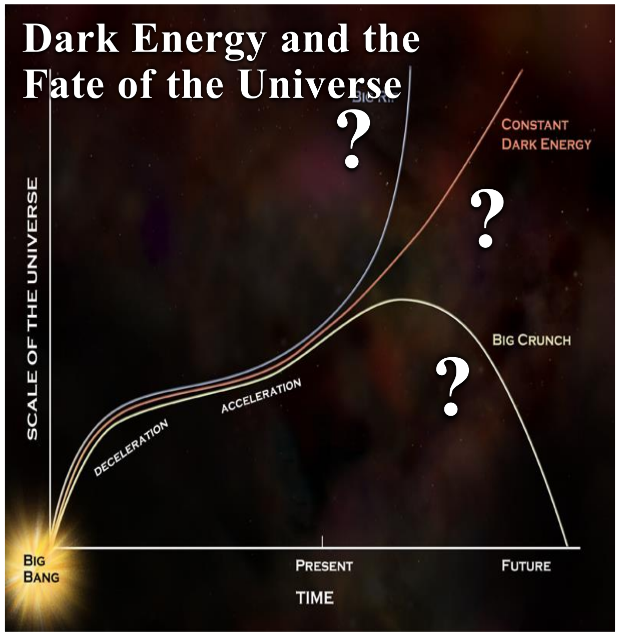
MPF

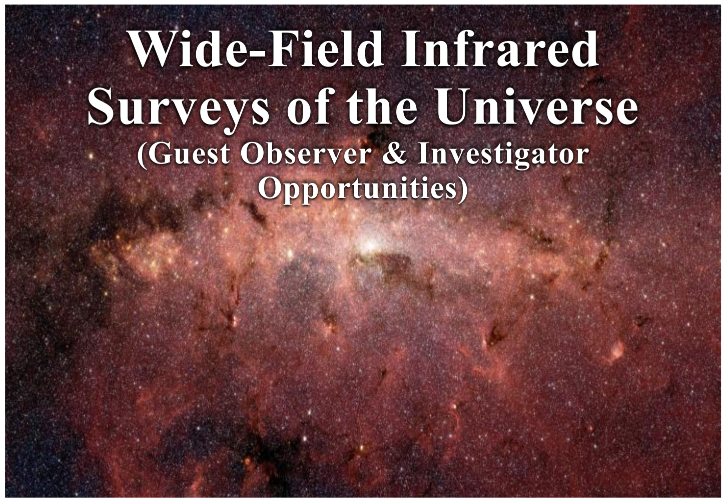
+

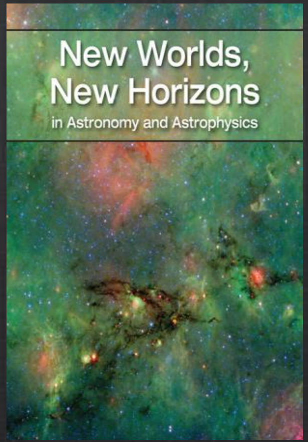


NIRSS

WFIRST Scientific Objectives

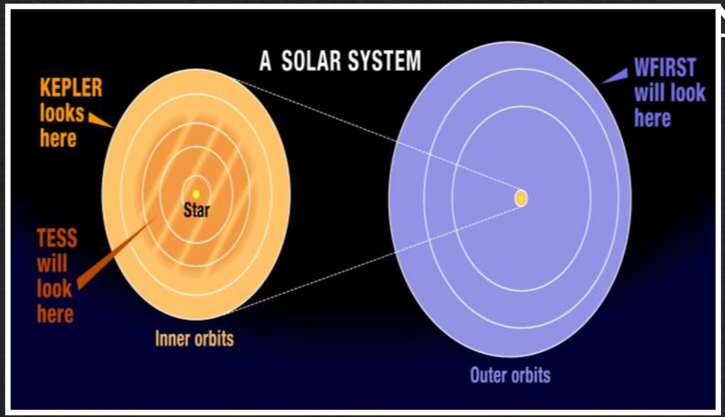






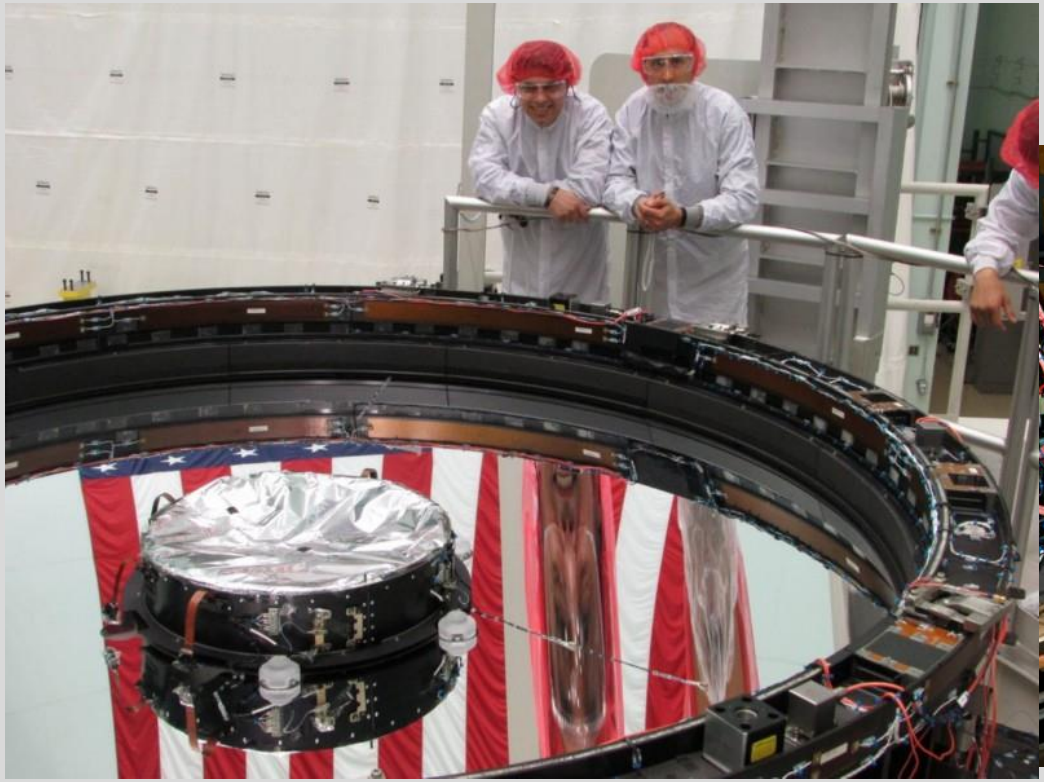
National Academy of Sciences
Astronomy & Astrophysics
Decadal Survey (2010)

The full distribution of planets around stars



WFIRST-AFTA

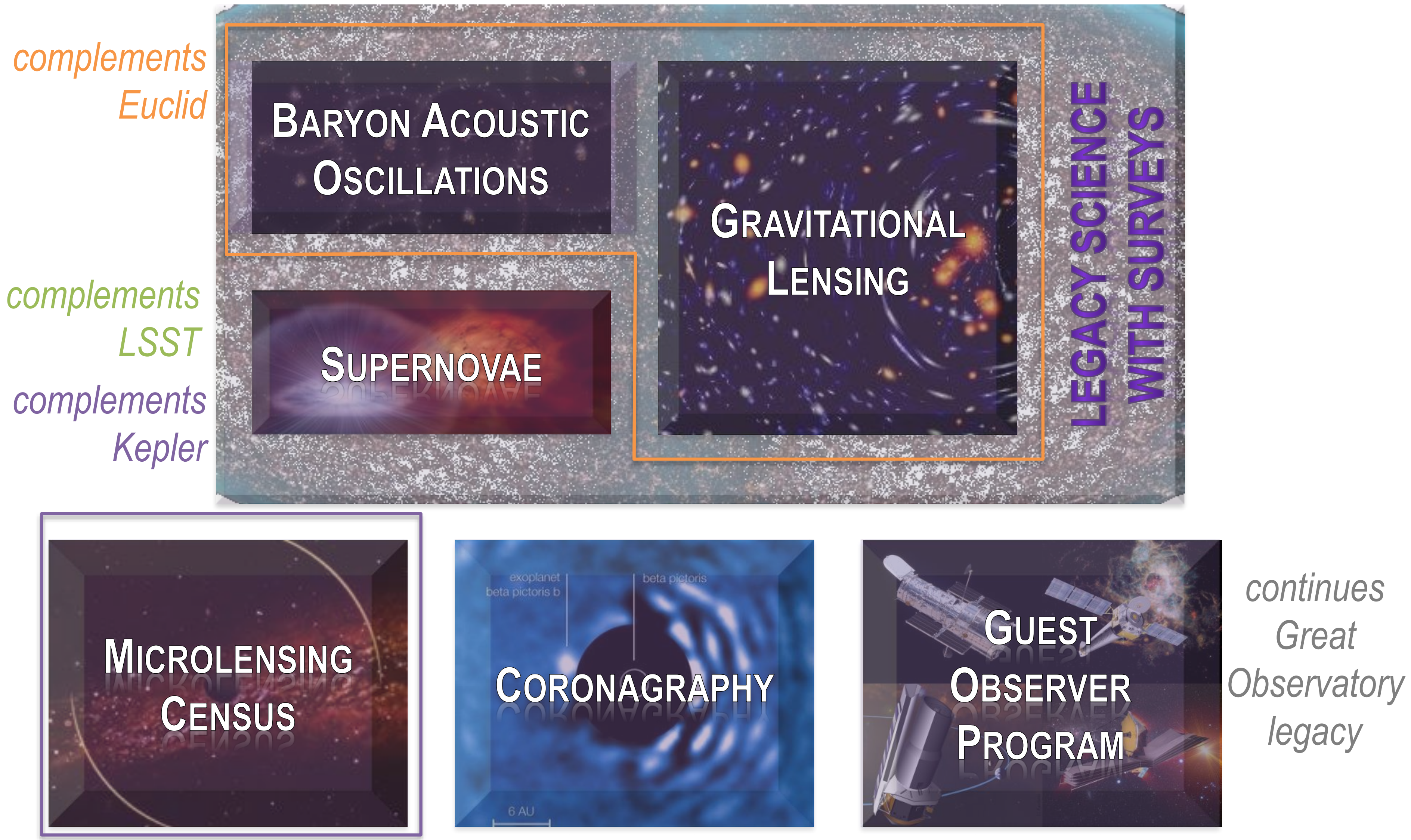
- WFIRST uses– **AFTA** (Astrophysics Focused Telescope Asset)
- AFTA is a repurposed 2.4 m telescope from the US National Reconnaissance office (NRO)
- The AFTA telescope is already built, and sitting in a storage facility



- WFIRST-AFTA includes a coronagraph to image exoplanets
- This was not envisaged by the decadal survey
- Enabled by the 2.4 meter mirror

Harris Corporation / TJT Photography

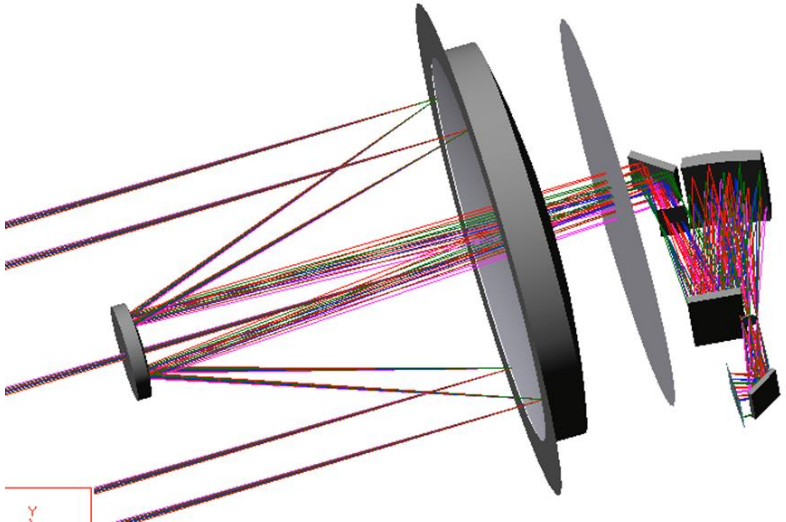
WFIRST Science

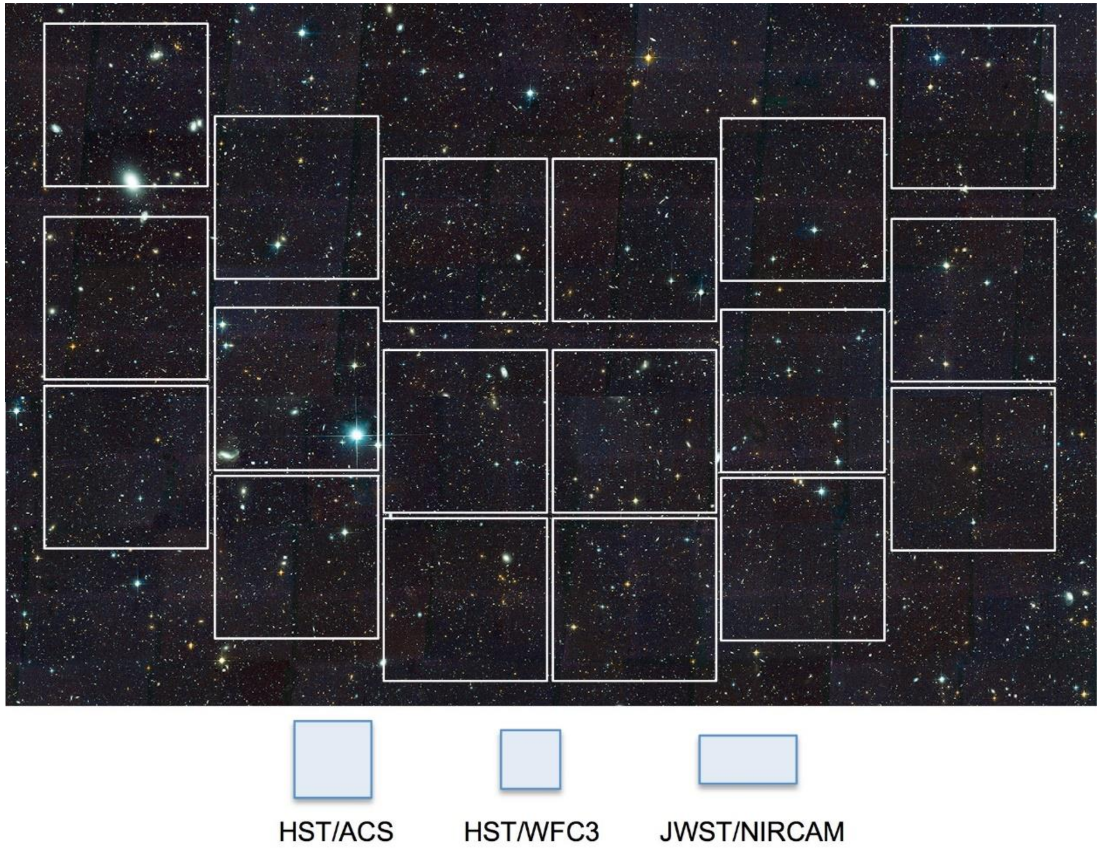


Wide Field Channel

- Very large imaging field of view (FOV) (0.8° x 0.4°)
- High spatial resolution (0.11 arcsec/pixel)

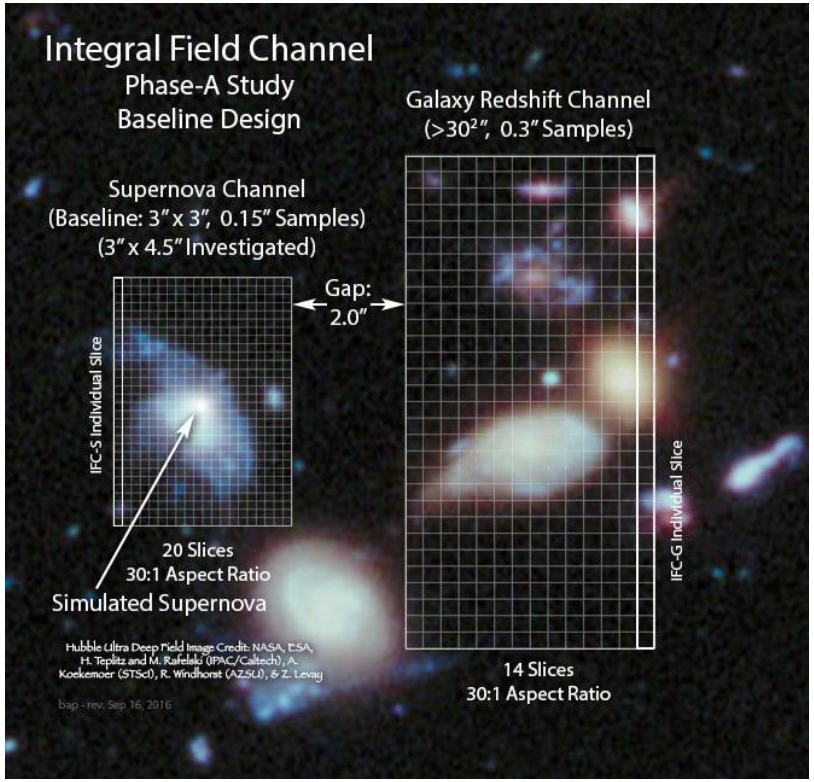
  - Stable image quality (1.0 nm RMS wave front error variation in 180 sec)
  - 7 imaging filters spanning visible & NIR: 0.48 to 2.0μm
  - grism for multi-object, low-resolution spectroscopy

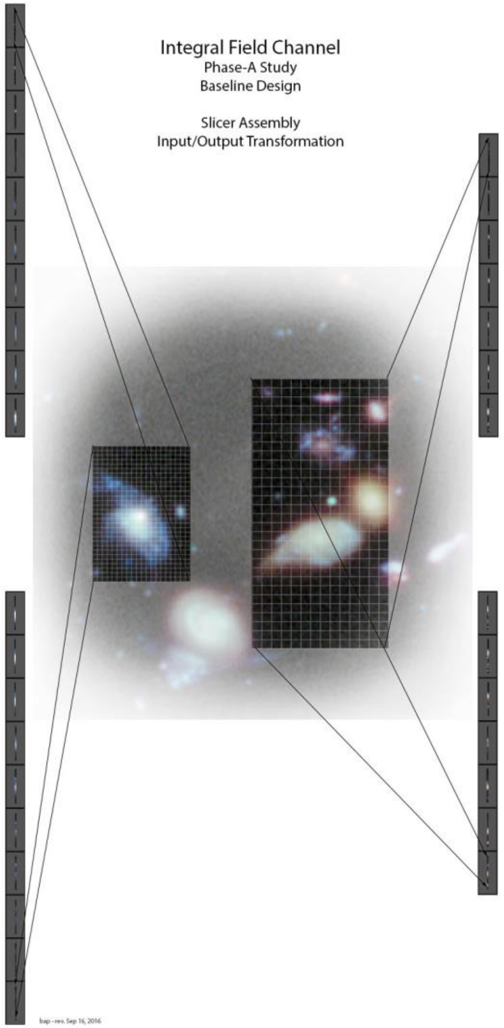




Integral Field Spectrograph

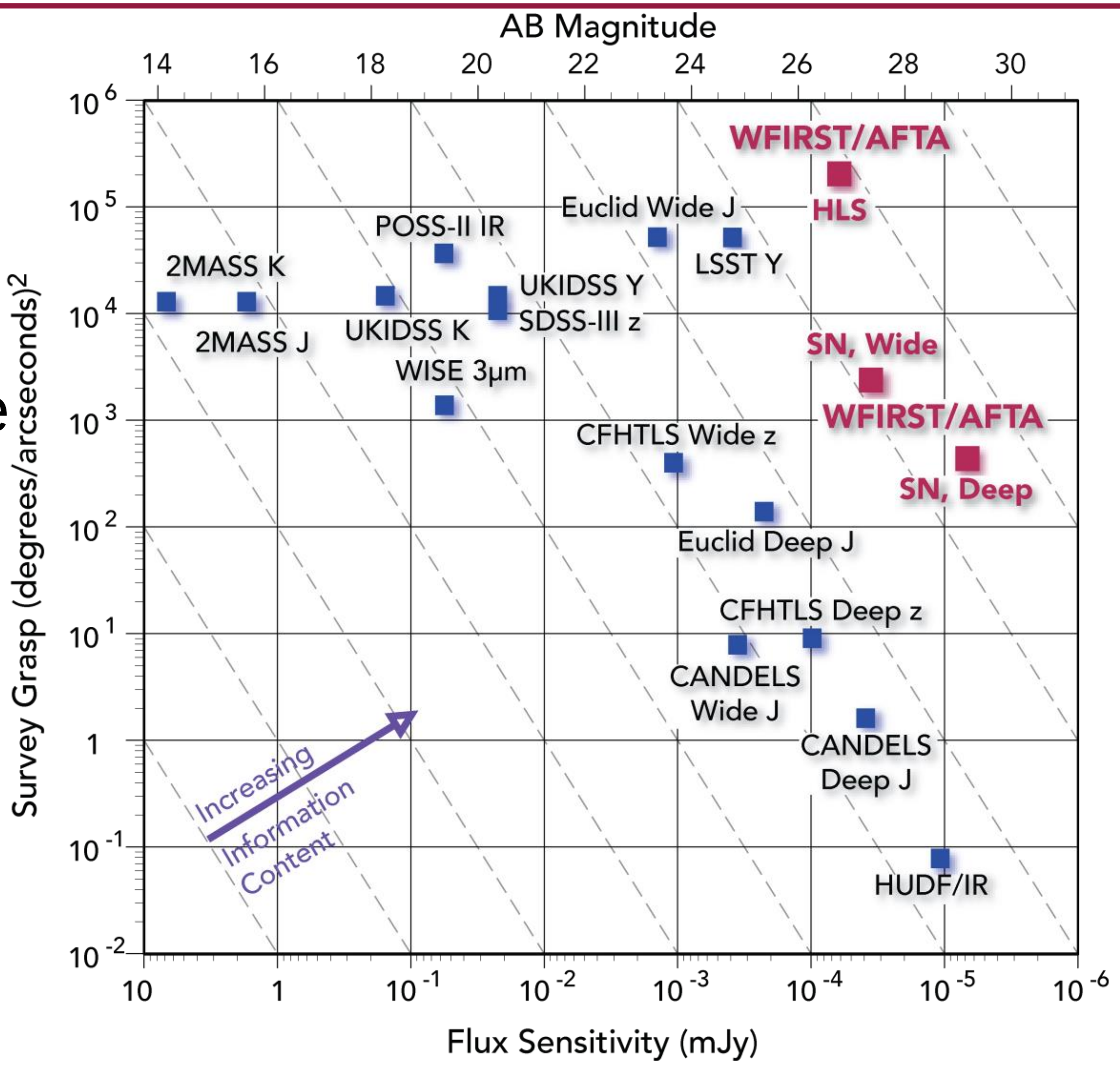
- Supernova FOV: 3 x 3 arcsec, 0.075 arcsec/pixel resolutio
- Photo-z Calibration FOV 6 x 6 arcsec, 0.15”/pixel resolutio
- Very high sensitivity, NIR pass band (0.45-2.0μm)
- Low spectral resolving power (70-140 λ/Δλ)





WFIRST Surveys

- Multiple surveys:
  - High-Latitude Survey
    - Imaging, spectroscopy, supernova monitoring
  - Repeated Observations of Bulge Fields for microlensing
  - 25% Guest Observer Program
  - Coronagraph Observations
- Flexibility to choose optimal approach



Near Infrared Surveys

Nominal Capabilities*

WFI:

Imager 0.76-2.0 microns 0.28˚ FoV, 0.11" pixel scale

Photo-z

Filters: R(0.48-0.76),Z (0.76 - 0.98), Y (0.93-1.19), J (1.13-1.45), H(1.38-1.77), F184 (1.68-2.0), W149 (0.93-2.00)

Shapes

Grism: 0.95-1.9 microns 0.28˚ FoV, R=461λ, 0.11" pixel scale

IFC: 0.6-2.0 microns 3" & 6" FoV, R~100, 0.075" pixel scale

Coronagraph:

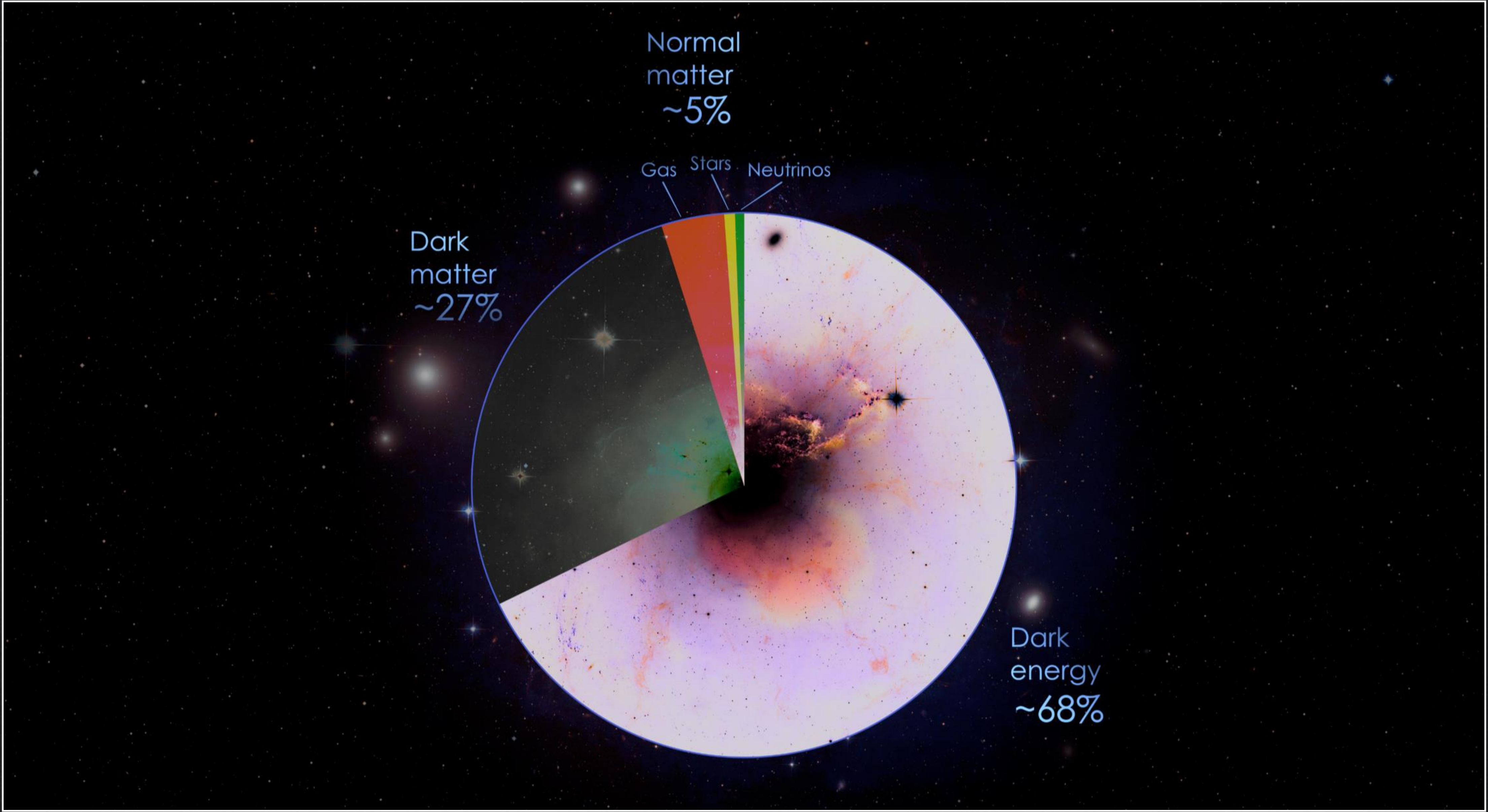
Imager: 0.43-0.97 microns 1.63" FoV (radius), 0.01" pixel scale, 1k x 1k EMCCD, 10^{-9} final contrast, 100-200 mas inner working angle

IFS: 0.60-0.97 microns 0.82" FoV (radius), R~70

Field of Regard: 54˚ - 126˚ 60% of sky available at any given time

*filters and exact wavelength ranges are still being optimized

The Universe as a Pie Chart



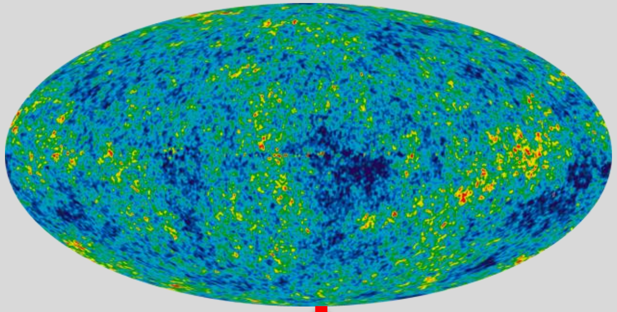
Top level questions

1. **Is cosmic acceleration caused by a new energy component or by the breakdown of General Relativity (GR) on cosmological scales?**

2. **If the cause is a new energy component, is its energy density constant in space and time, or has it evolved over the history of the universe?**

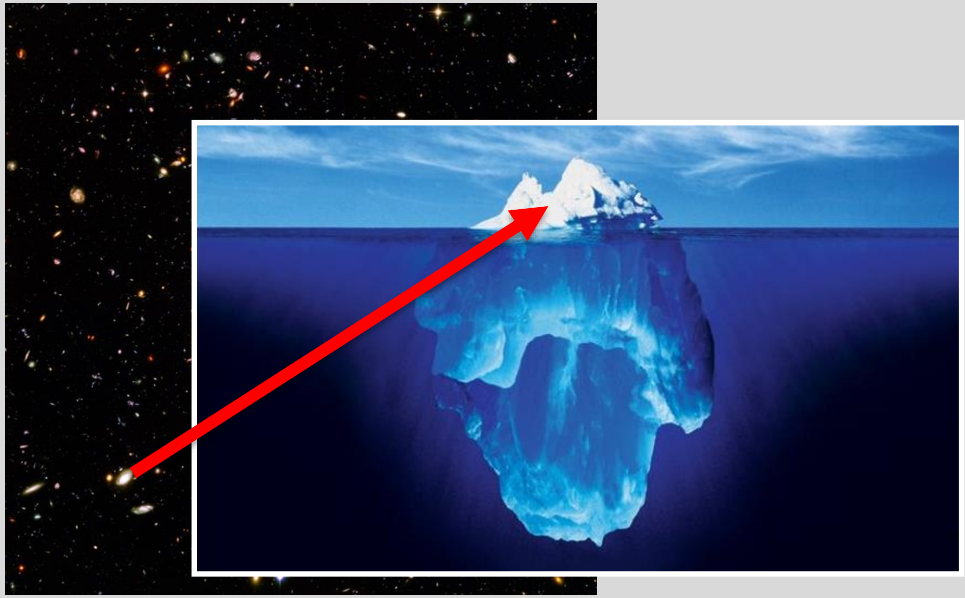
Consequences of DE

Dark Energy affects the:



- Expansion history of the Universe
  - How fast did the Universe expand?
  - Also called the geometry of the Universe

- Growth of structures
  - How do structures (which are mostly dark matter) evolve and grow over time
  - Attractive gravity competes with repulsive dark energy



If Einstein's General Relativity is wrong, modified gravity theories could explain the accelerating expansion.

This would change the above effects differently, *so we must measure them both!*

Probes of DE

Comparison of expansion history and growth of structure helps distinguish dark energy and modified gravity models

- Supernovae type IA, which act as standard candles to measure the expansion history
- Weak gravitational lensing, the apparent distortion of galaxy shapes by foreground dark matter
  - Measures primarily growth of structure
- Galaxy clustering
  - Baryon acoustic oscillations (BAO), which act as a standard ruler to measure the expansion history
  - Redshift space distortions (RSD) which measure the growth of structure

Dark energy studies are done statistically, and require great precision and attention to systematics

Wide field space mission is required

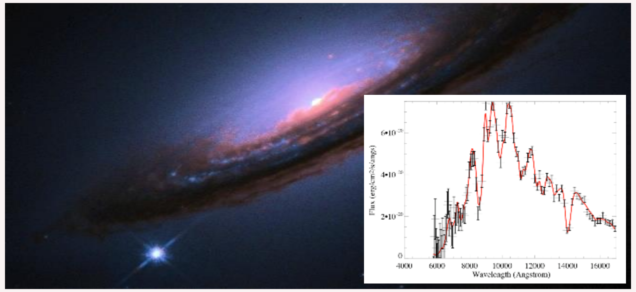
WFIRST Dark Energy Roadmap

Supernova Survey

wide, medium, & deep imaging
+
IFU spectroscopy

2700 type Ia supernovae
z = 0.1–1.7

standard candle distances
z < 1 to 0.20% and z > 1 to 0.34%



High Latitude Survey

spectroscopic: galaxy redshifts

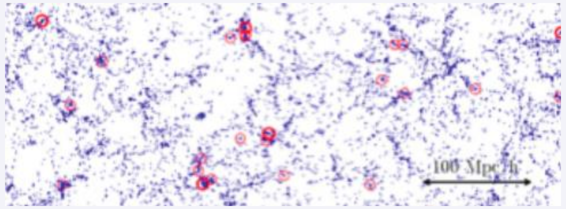
16 million Hα galaxies, z = 1–2
1.4 million [OIII] galaxies, z = 2–3

imaging: weak lensing shapes

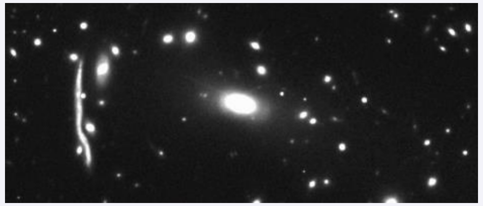
380 million lensed galaxies
40,000 massive clusters

standard ruler

distances	expansion rate
z = 1–2 to 0.5%	z = 1–2 to 0.9%
z = 2–3 to 1.3%	z = 2–3 to 2.1%

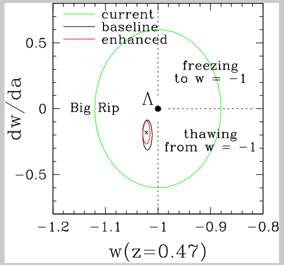


dark matter clustering
z < 1 to 0.21% (WL); 0.24% (CL)
z > 1 to 0.78% (WL); 0.88% (CL)
1.1% (RSD)



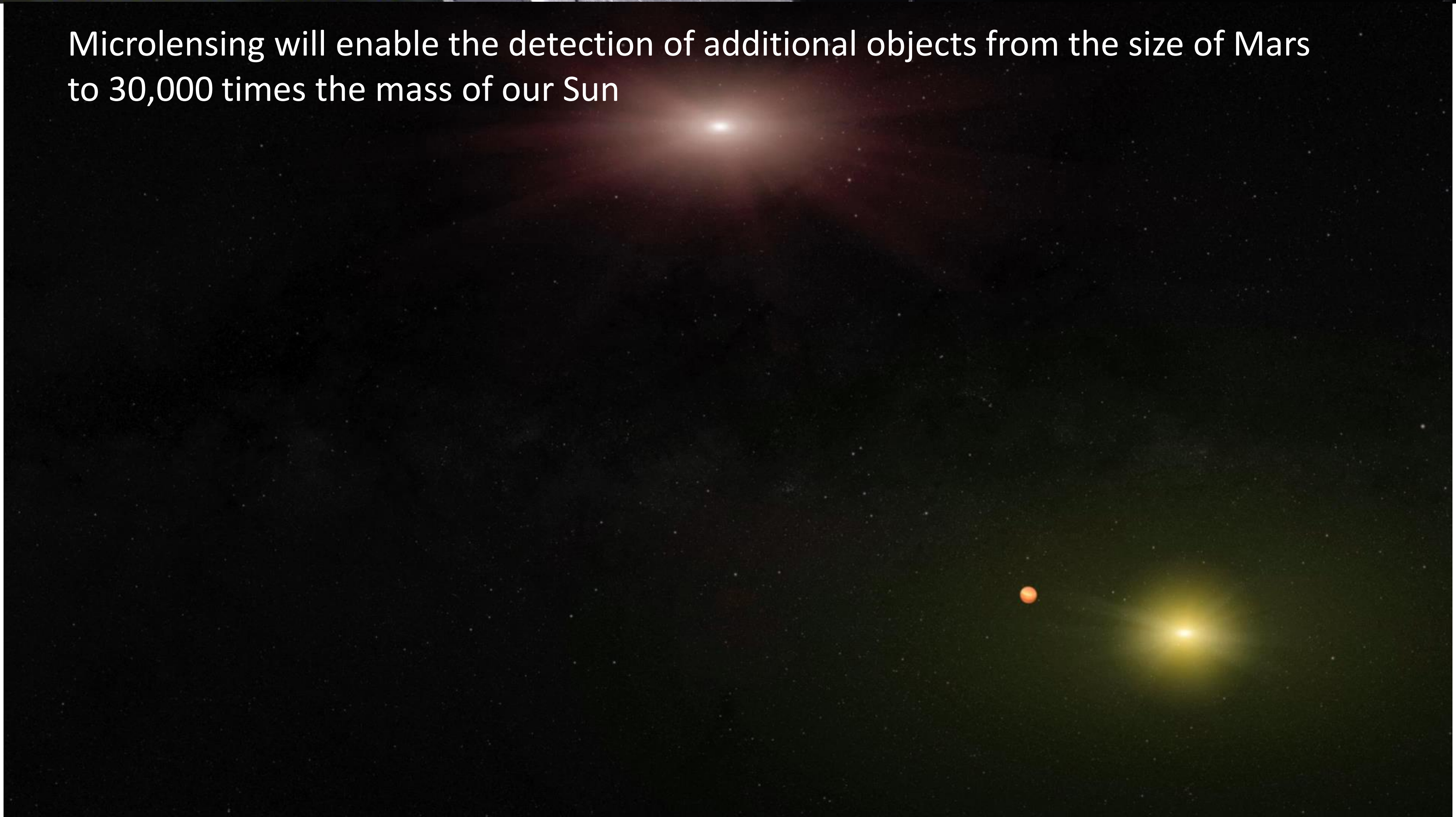
history of dark energy
+
deviations from GR

w(z), ΔG(z), Φ_{REL}/Φ_{NREL}

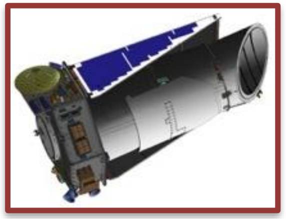


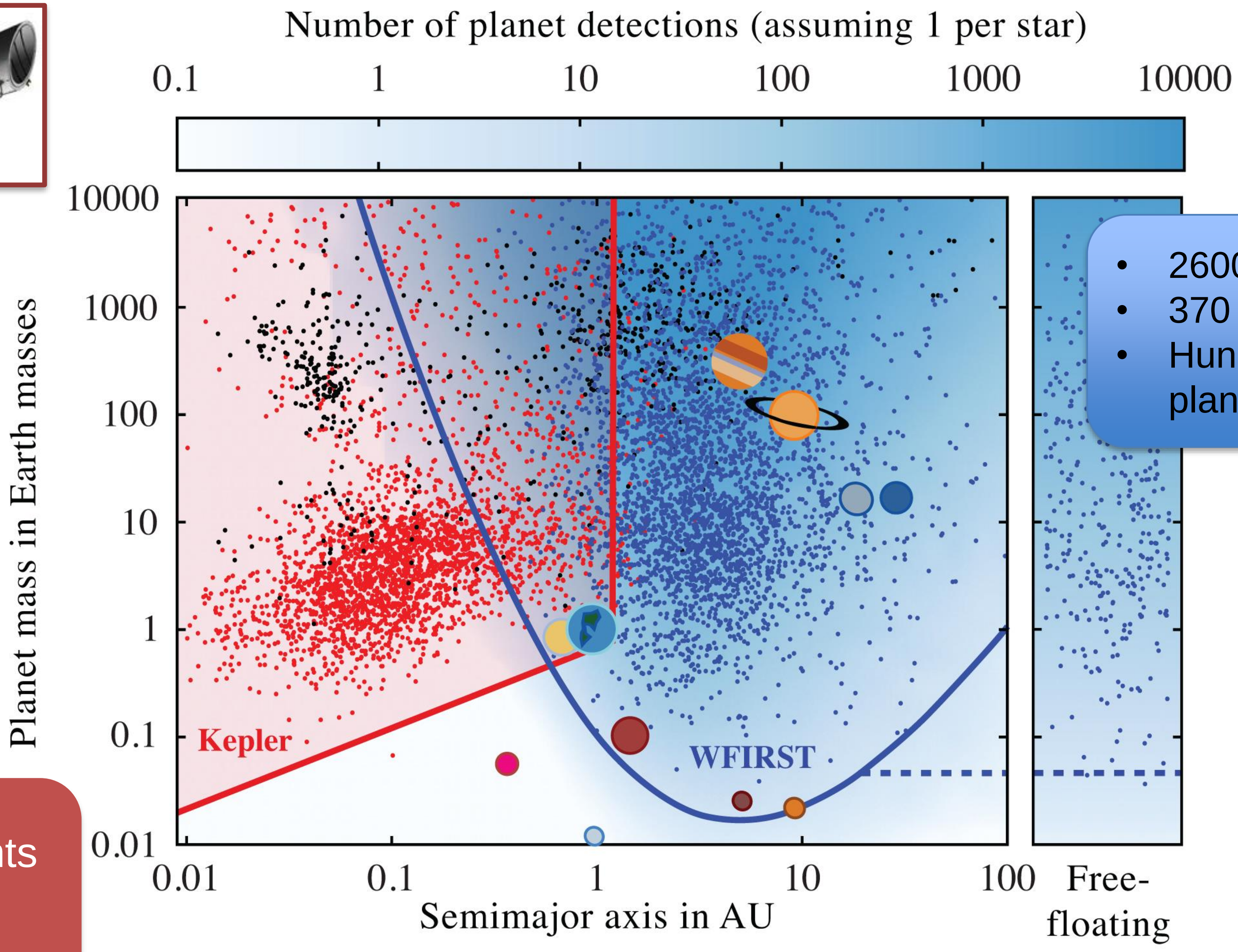
Microlensing

Microlensing will enable the detection of additional objects from the size of Mars to 30,000 times the mass of our Sun



Exoplanet Surveys
Kepler & WFIRST



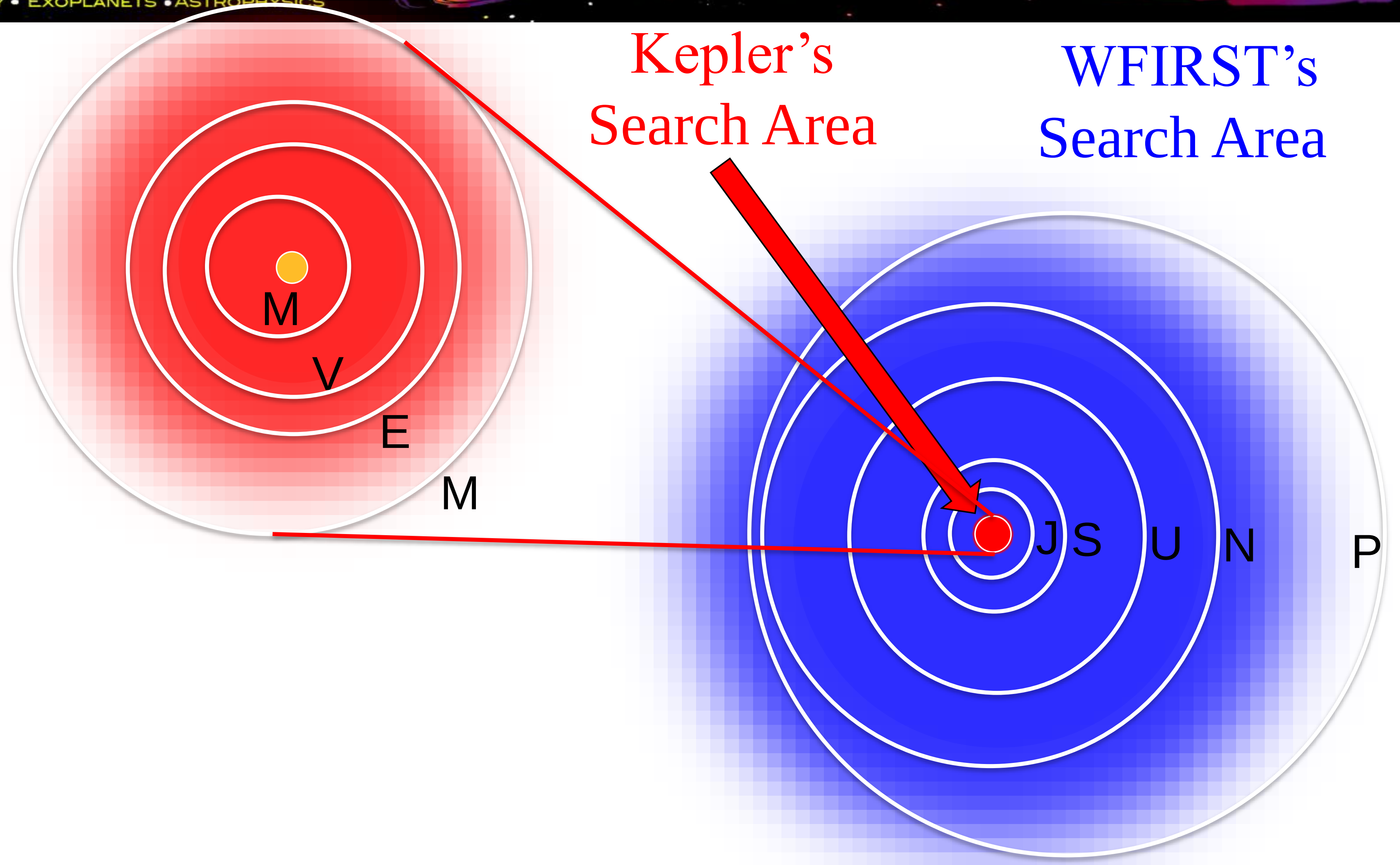


- 2600 planet detections.
- 370 with Earth mass and below.
- Hundreds of free-floating planets.

WFIRST complements Kepler, TESS, and PLATO.

M. Penny (OSU)

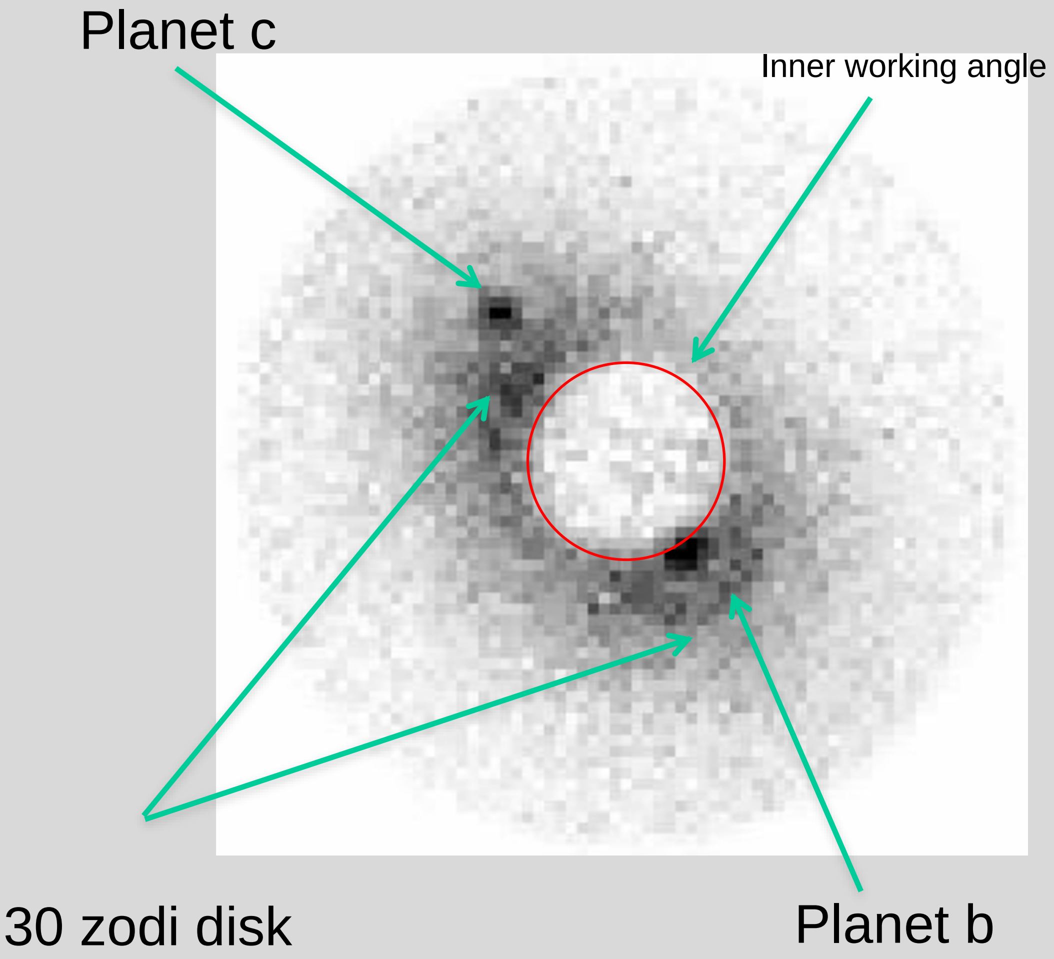
WFIRST Complements Kepler



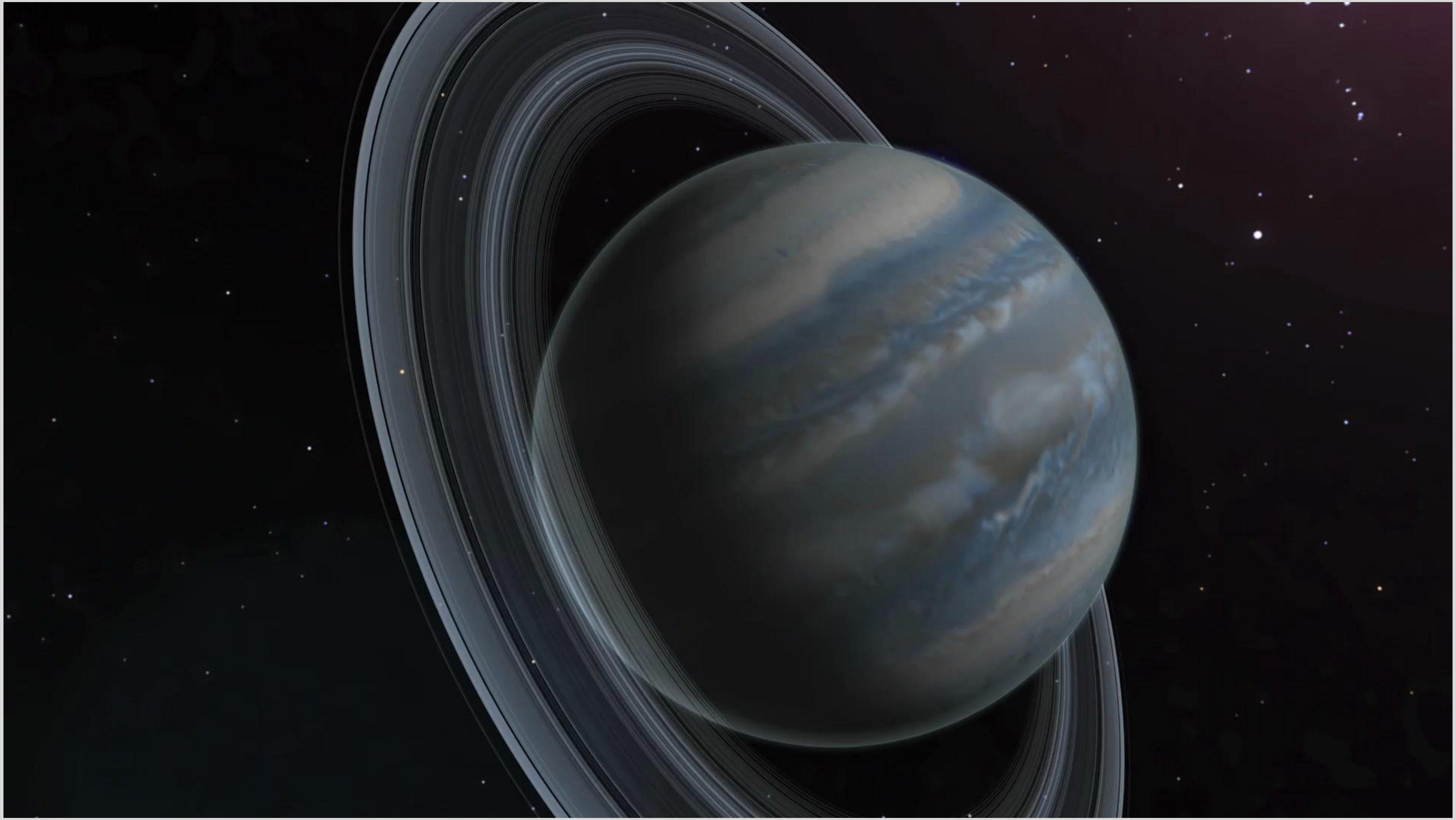
Coronagraphy

- **A coronagraph 'blocks' light from a host star, enabling light from an exoplanet to enter the detector**

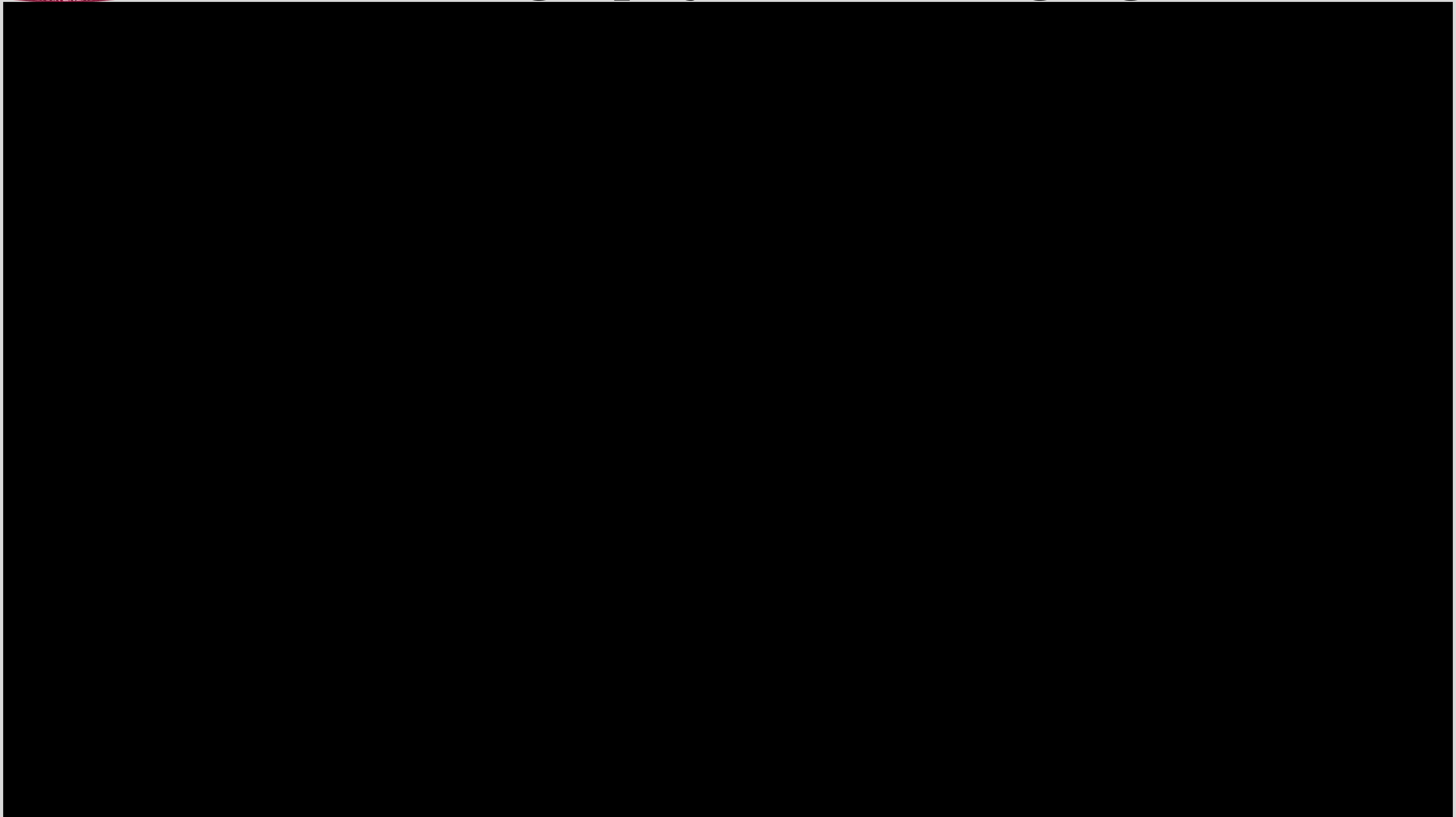
- **The contrast between a host star and the planets is large**



Coronagraphy



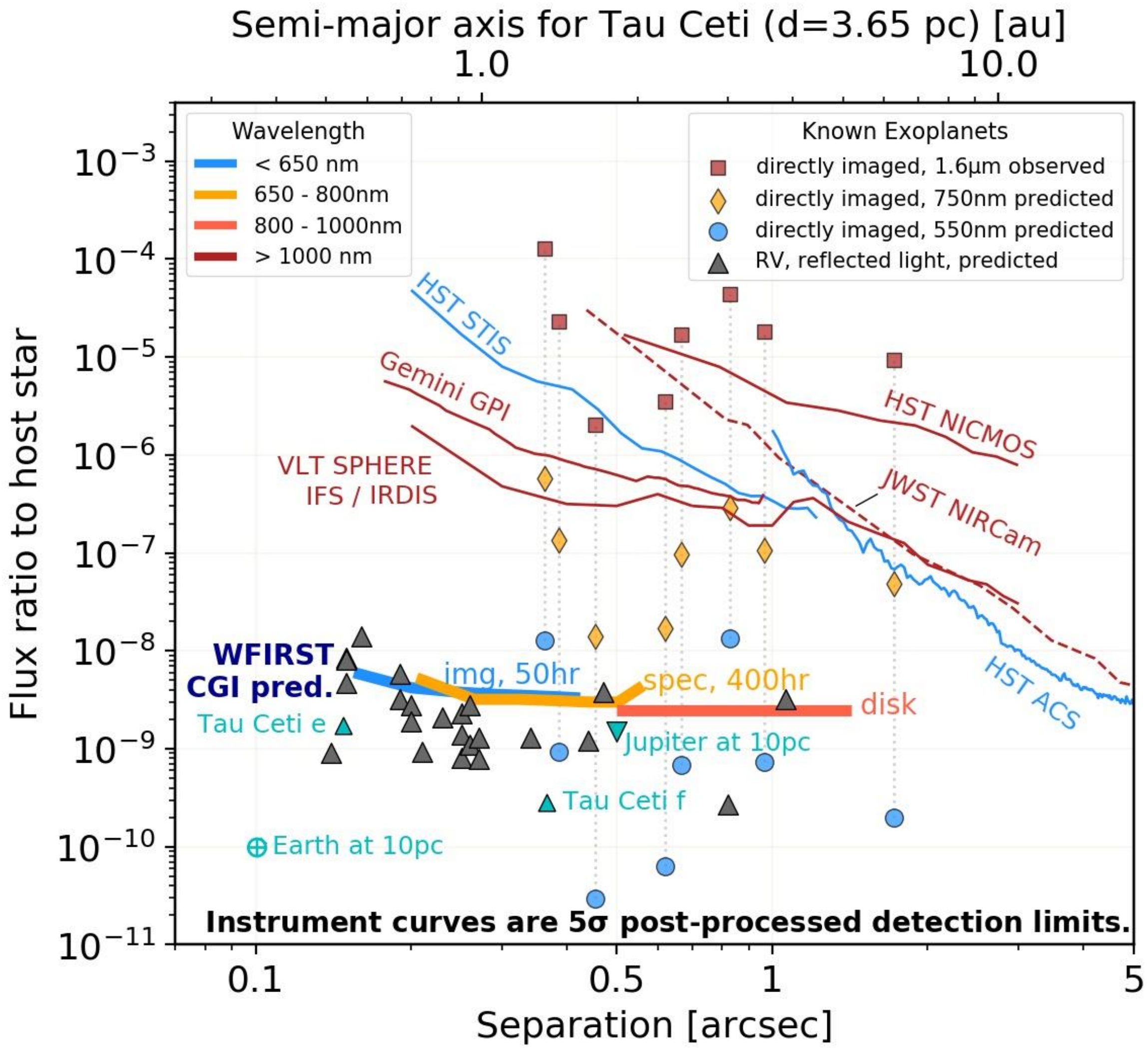
Coronagraphy is Challenging



Powers of 10

- Current best coronagraphs reach a contrast ratio of $10^{6\text{-}7}$
- WFIRST requirements are for 10^{9}
- All technological milestones have been hit ahead of schedule and 10^{8} has been shown in lab
- WFIRST will test two different types of coronagraphs for both spectroscopy (shaped pupil) and photometry (hybrid Lyot)
- What we need for direct imaging of an exo-Earth to show biomarkers is probably 10^{10}
- The Astro 2020 Decadal Survey will look at HabEx and LUVOIR, two mission concepts that might be able to do this

Coronagraph Performance



WFIRST CGI Science Yield vs Instrument Performance: Exo-planetary systems

- With ~3×10^{-9} contrast at 0.2″, WFIRST CGI will:
  - Get first optical images of ~10 known RV EGPs orbiting mature sun-like stars
  - Get first reflected (albedo) spectra of a few of them
  - Image faint debris disks structures down to a level of ~40 times that of our solar system's zodiacal dust, in and exterior to the HZ
  - Get first optical images and optical spectra of known young EGPs, constraining their metallicity, formation process, and mass

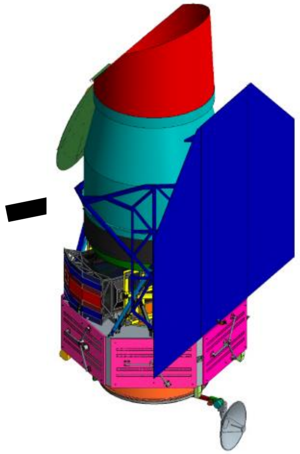
- With 10^{-8} contrast at 0.2″, WFIRST CGI will:
  – Possibly get first optical images of a few known giant RV planets orbiting mature sun-like stars
  – Image faint debris disks structures down to a level of ~100 times that of our solar system's zodiacal dust, in and exterior to the HZ
  – Get first optical images and first optical spectra of known young giant exoplanets, providing information about temperature and physical properties

Science \ Contrast	10^{-9}	3×10^{-9}	10^{-8}	10^{-7}
Cool EGPs optical spectra	Yes (10+)	A few	No	No
Cool EGPs optical Images	Yes	Yes	Possibly	No
Young EGPs optical spectra	Yes	Yes	Yes	Some
Young EGPs optical images	Yes	Yes	Yes	Some
Exo-Zodi Disks optical images	10 zodis	40 zodis	~100 zodis	1000 zodis

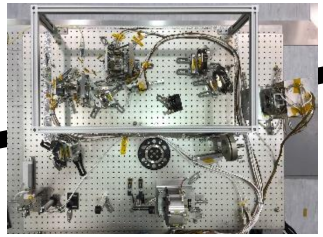
Table from B. Mennesson

Coronagraph technology development

Large Ultra-stable Space Telescope & Observatory

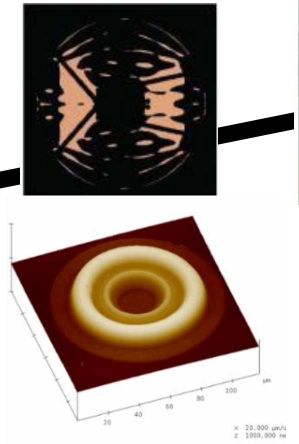


Autonomous Ultra-Precise Wavefront Sensing & Control System



First Use of Deformable Mirrors in Space

High Contrast Coronagraph Masks



Ultra-low Noise Photon Counting Visible Detectors

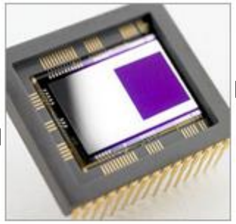
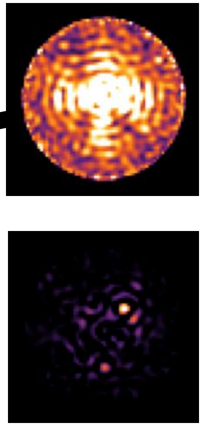
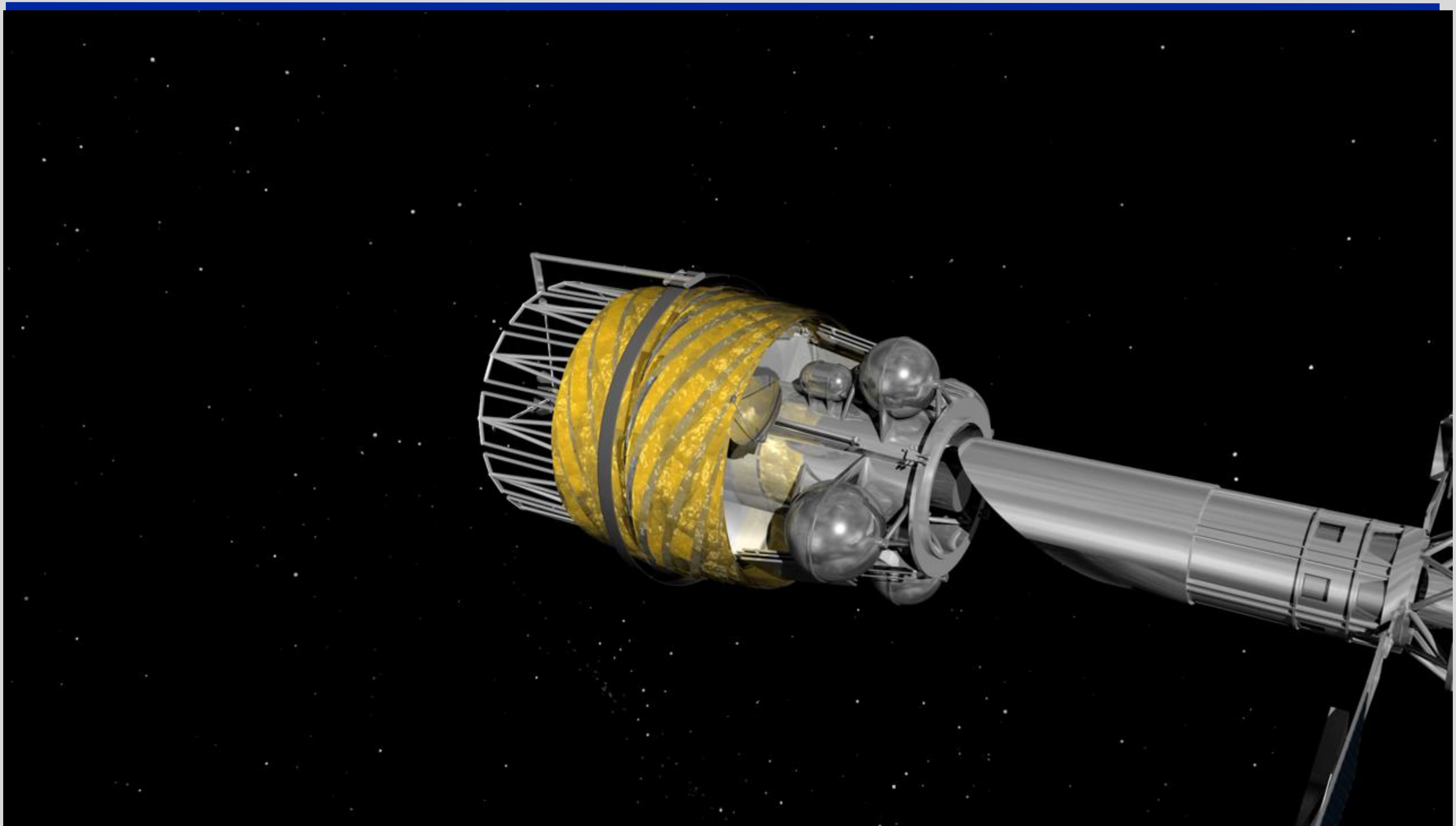


Image Processing at Unprecedented Contrast Levels

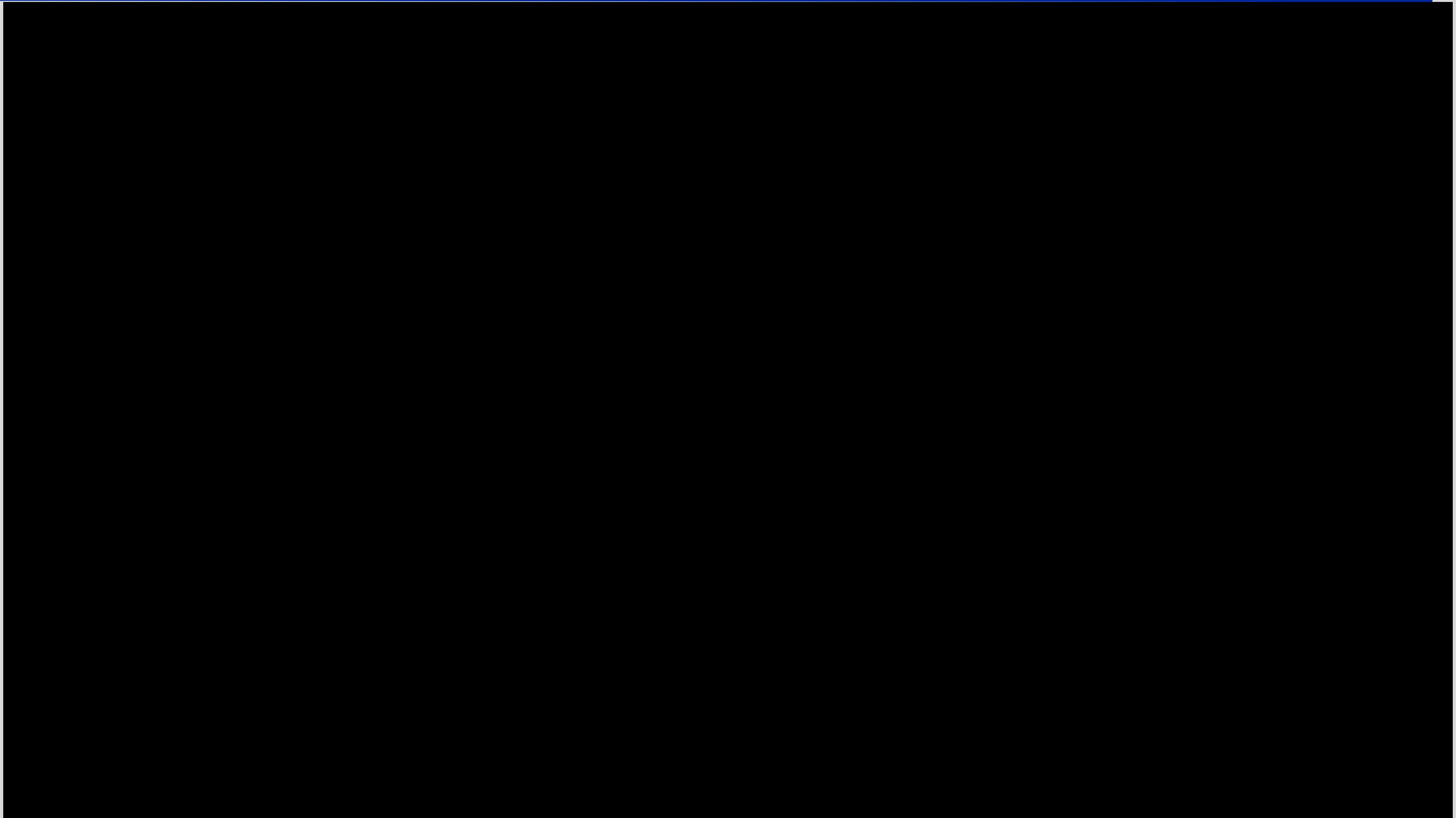


CGI is a direct predecessor to potential future flagship direct imaging missions aimed at *Earth-like* exoplanets (HabEx and LUVOIR)

Starshade



Starshade at JPL



WFIRST Observing Plan (nominal)

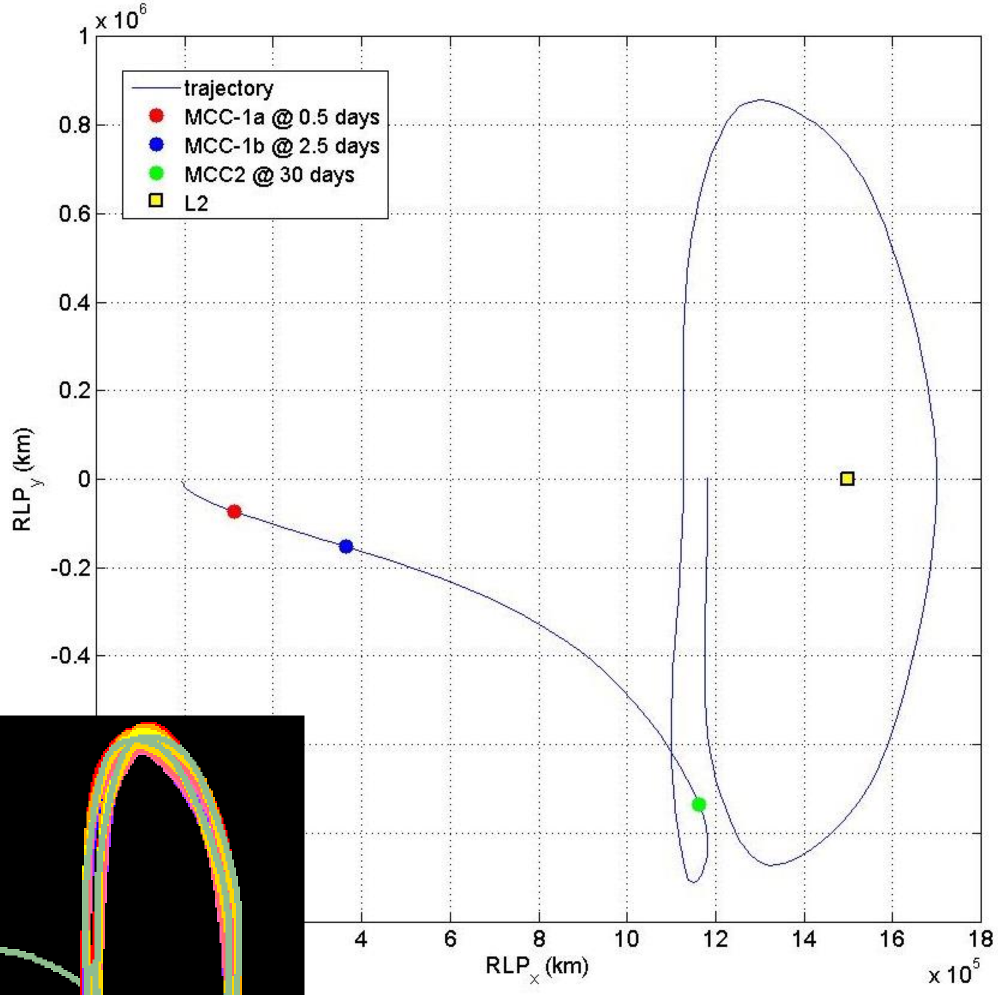
WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
DARK ENERGY • EXOPLANETS • ASTROPHYSICS

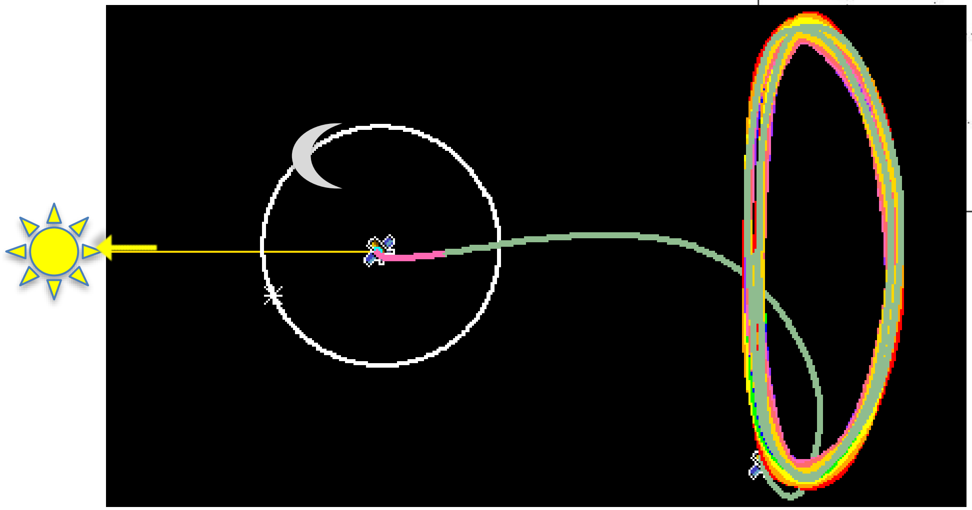
- High Latitude Survey - ~2000 sq deg
  - Imaging: Y, J, H, F184 to AB ~26.5 (5σ point src)
  - Slitless spectroscopy: 1.e-16 ergs/cm^2/s
- Supernovae
  - Imaging & IFC spectroscopy (6 months)
- Microlensing
  - Six Galactic Bulge seasons
- Coronagraphy
  - Technology demonstration, plus ???
- GO
  - 1.25 years – the sky is the limit!

- *This is just one DRM example of how the WFIRST Science Campaigns could be conducted*
- *Notional durations obtained using first-order, simplistic models*
  - Serial execution of all science campaigns
  - Using the baseline science requirements (BSRs)
- *Updates to higher-fidelity models in-progress to refine notional duration estimates*
  - Affords opportunities to explore science scheduling efficiencies and parallel (WFI & CGI) science observations
  - Uses candidate science targets, proper orbital geometries and science campaign characteristics

Planned Sun-Earth L2 halo orbit

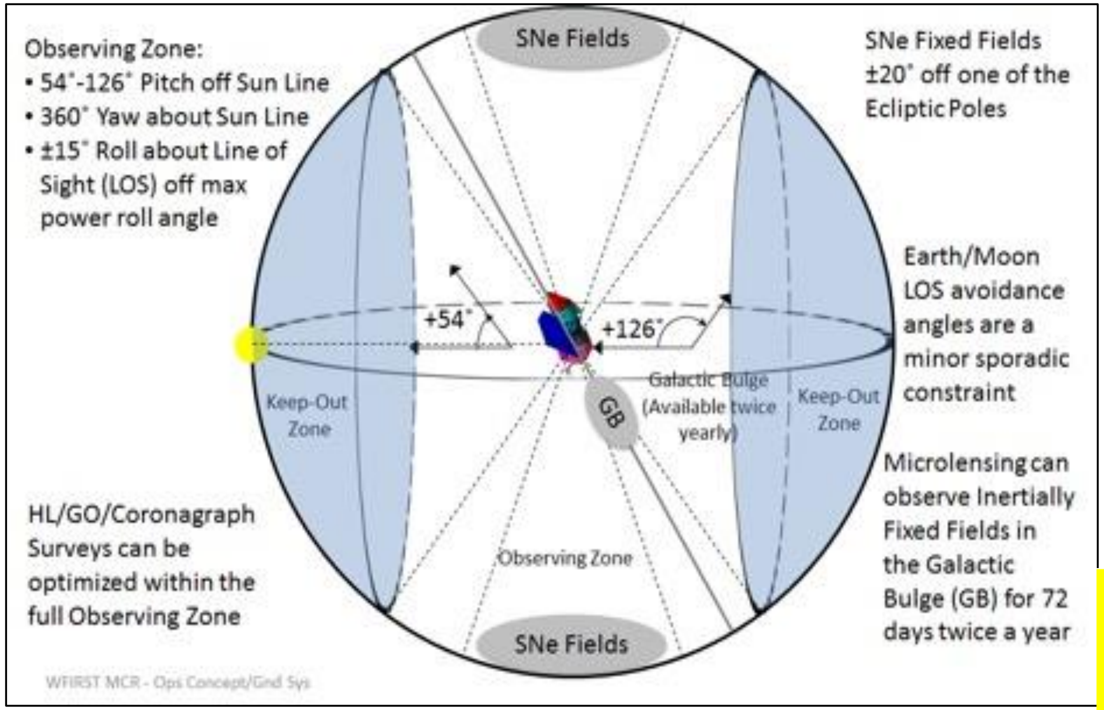
Diameter of planned halo orbit is comparable to Earth-L2 distance

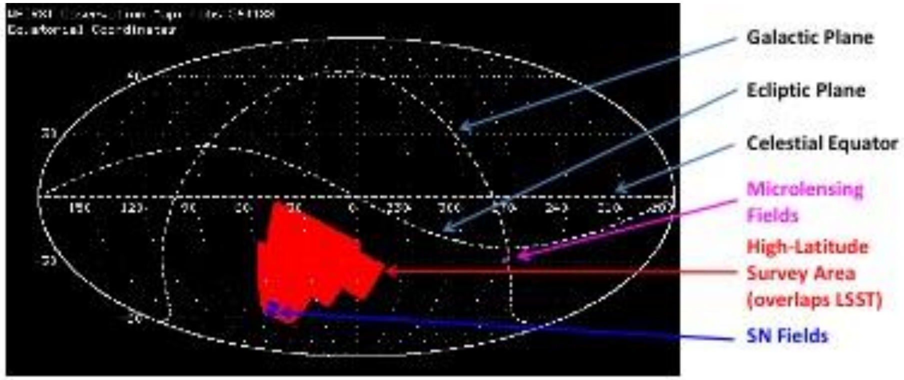




Mission Design Elements

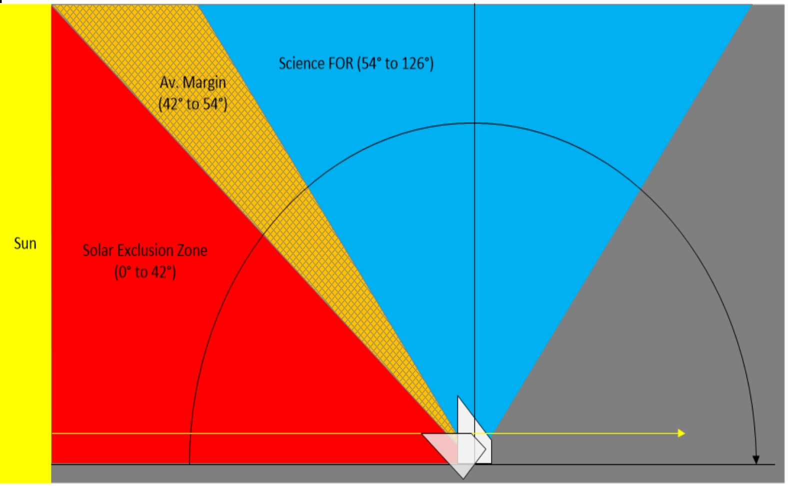
Field of Regard



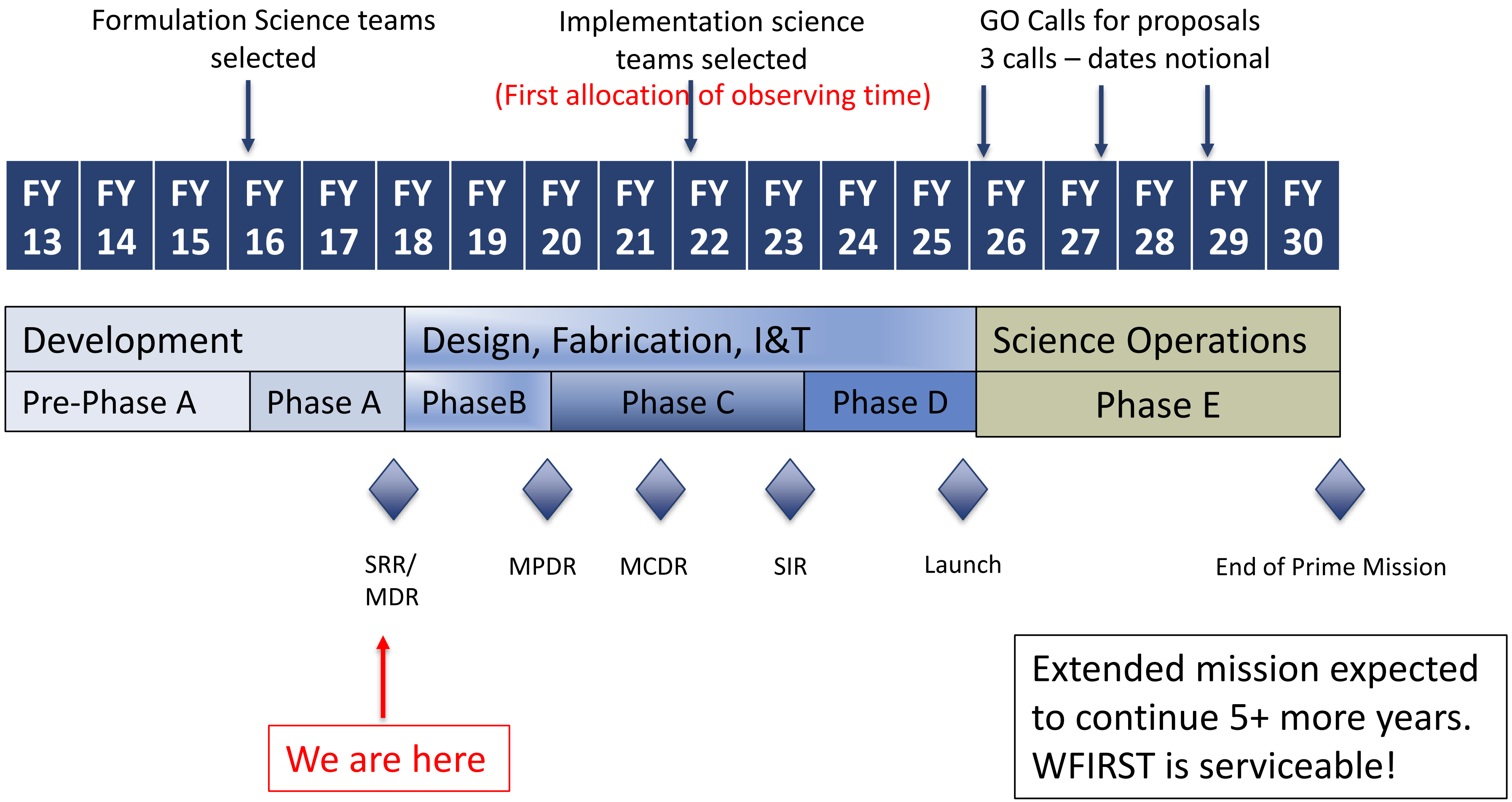


Field Of Regard (FOR)

- Based on Science Needs
- Considers launch vehicle constraints, power and thermal performance
- Figure below incorporates the solar exclusion zone and ACS margin zone
- **No changes anticipated**



Project Schedule



Opportunities with WFIRST

- 25% Guest Observer in 5 year prime mission
- ~100% GO in extended mission
- Guest Investigator calls throughout mission
- All prime survey science teams will be competed in ~2021
- 2020 Decadal Survey will consider a Probe class Starshade

Extra Slides

WIRST FSWG

Jeff Kruk GSFC Project Scientist, **Chair**
Jeremy Kasdin Princeton U. CGI Adjutant Scientist, Co-Chair
David Spergel Princeton U. WFI Adjutant Scientist, Co-Chair

SCIENCE TEAM PIs
Olivier Doré JPL Weak Lensing, Redshift Survey
Ryan Foley U. Illinois Supernovae
Scott Gaudi Ohio State U. Microlensing
Jason Kalirai Johns Hopkins U. GO, Milky Way Science
Bruce Macintosh Stanford U. Coronagraph
Saul Perlmutter LBNL Supernovae
James Rhoads Arizona State U. GO, Cosmic Dawn
Brant Robertson UC Santa Cruz GO, Extragalactic Science
Alexander Szalay Johns Hopkins U. GI, Archival Science
Margaret Turnbull SETI Institute Coronagraph
Benjamin Williams U. Washington GO, Nearby Galaxies

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Roc Cutri Caltech/IPAC Science Center
Jason Rhodes JPL WFIRST Project Scientist
Roeland van der Marel STScI Science Center

SCIENCE TEAM DEPUTIES
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Chris Hirata Ohio State U. Weak Lensing, Redshift Survey
Nikole Lewis STScI Coronagraph
Aki Roberge GSFC Corongraph
Yun Wang Caltech/IPAC Weak Lensing, Redshift Survey
David Weinberg Ohio State U. Weak Lensing, Redshift Survey

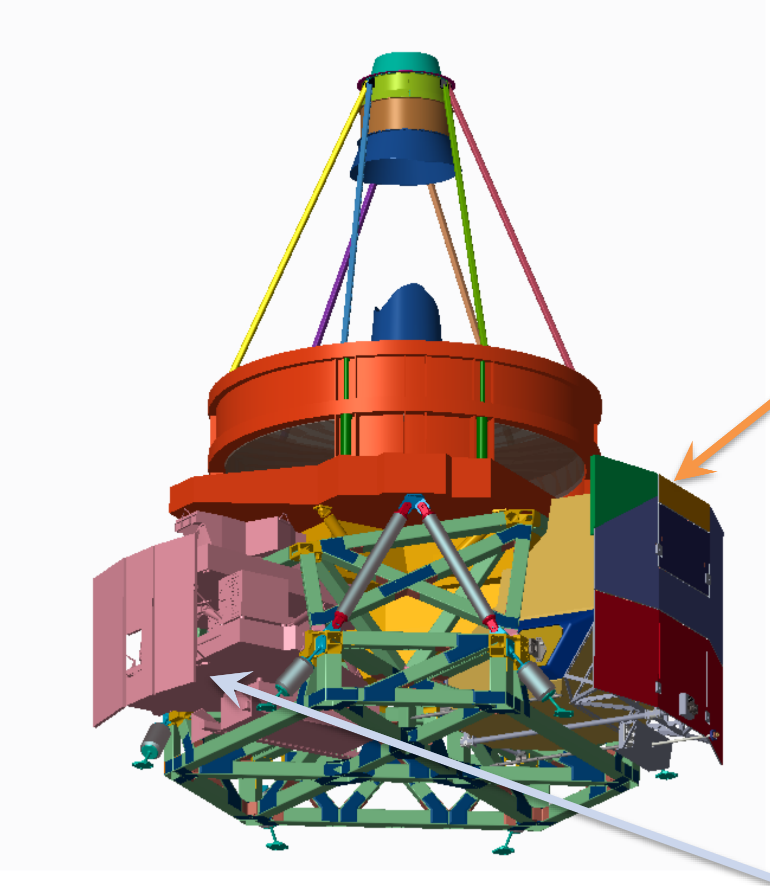
INTERNATIONAL OBSERVERS
Anthony Boccaletti ESA Representative
Jean Dupuis CSA Representative
Thomas Henning ESA Representative
Toru Yamada JAXA Representative

WFC filters

Band	Element name	Min (µm)	Max (µm)	Center (µm)	Width (µm)	R
R	R062	0.48	0.76	0.620	0.280	2.2
Z	Z087	0.76	0.977	0.869	0.217	4
Y	Y106	0.927	1.192	1.060	0.265	4
J	J129	1.131	1.454	1.293	0.323	4
H	H158	1.380	1.774	1.577	0.394	4
	F184	1.683	2.000	1.842	0.317	5.81
Wide	W146	0.927	2.000	1.464	1.030	1.42
GRS	G150	0.95*	1.90*	1.445	0.890	461λ(2pix)

* Grism bandpass is adjustable, up to $\lambda max \leq 2\times\lambda min$

WFIRST Instruments



Wide-Field Instrument

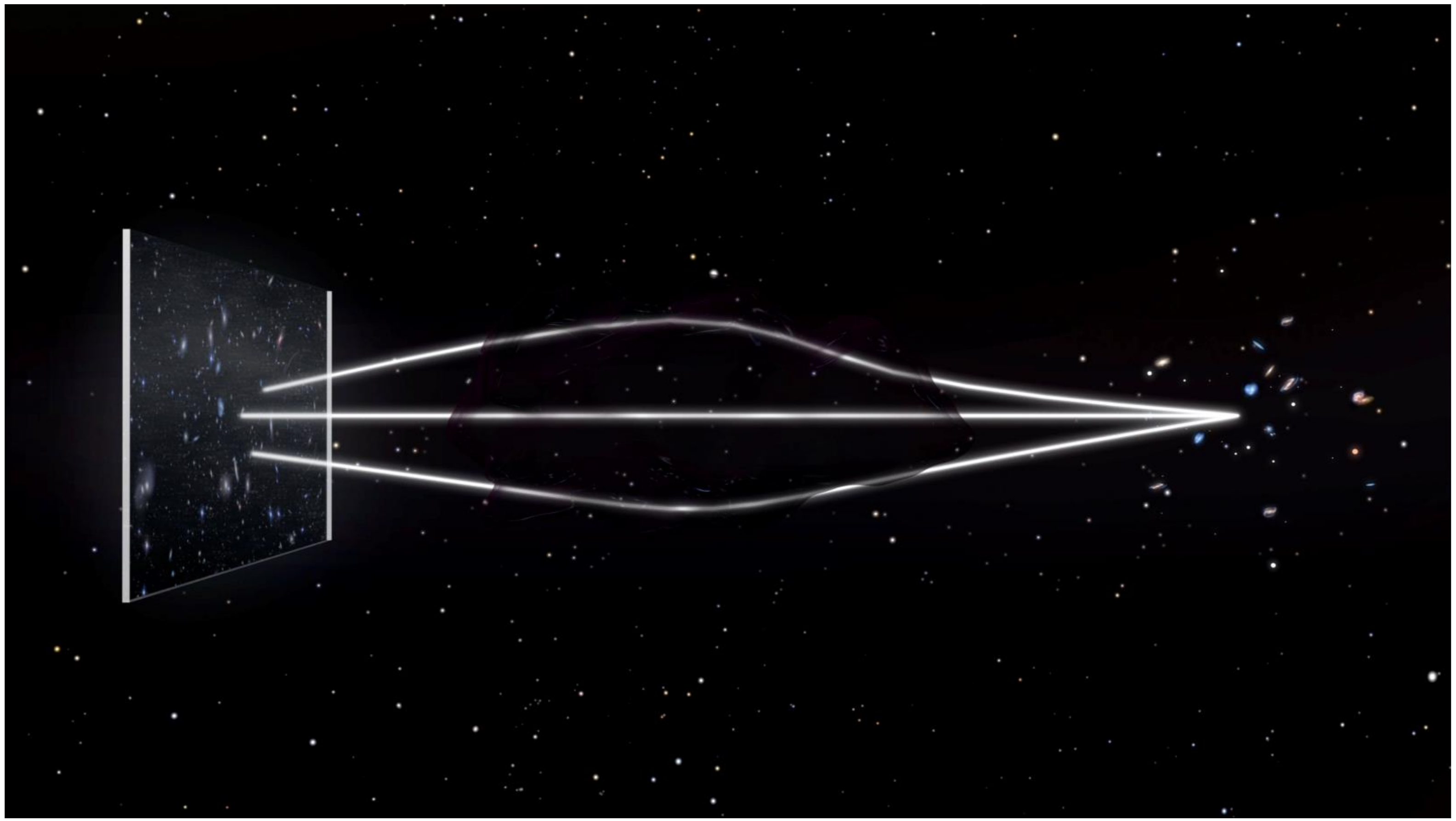
- *Imaging & spectroscopy over 1000s of sq. deg.*
- *Monitoring of SN and microlensing fields*
- 0.5 – 2.0 μm (imaging) & 1.0-1.9 μm (grism)
- 0.28 deg^2 FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 7 filter imaging, grism + IFU spectroscopy

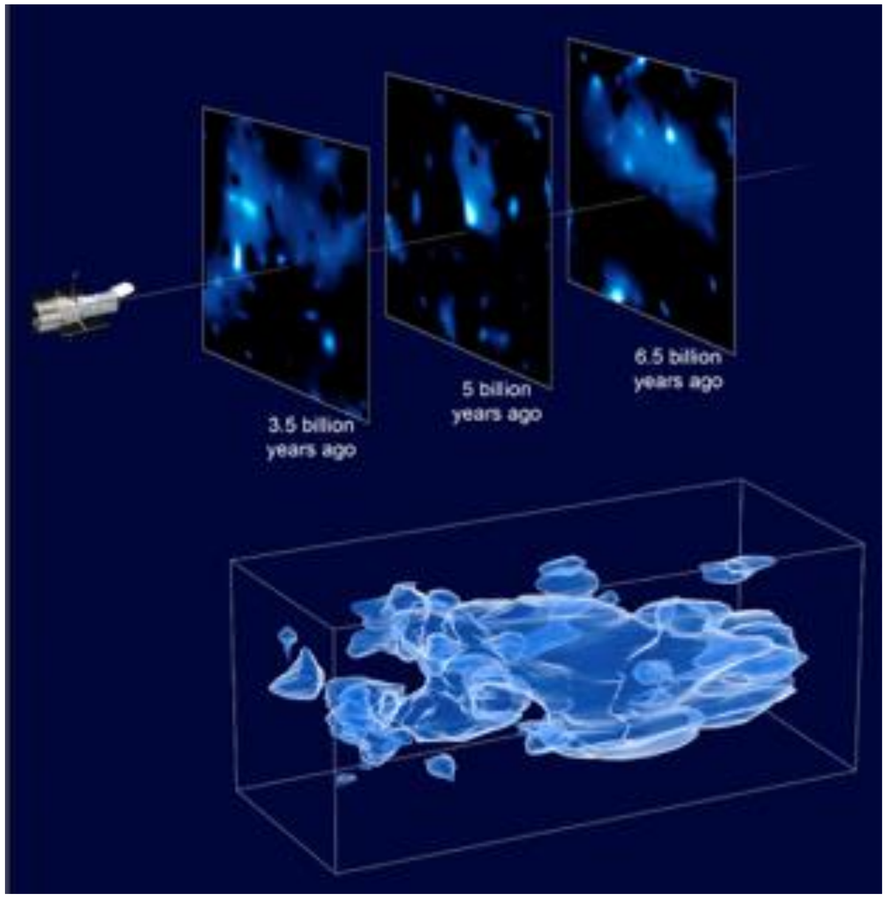
Coronagraph

- *Image and spectra of exoplanets from super-Earths to giants*
- *Images of debris disks*
- 430 – 970 nm (imaging) & 600 – 970 nm (spec.)
    - *Under revision: tech demo configuration TBD*
- Final contrast of 10^{-9} or better
- Exoplanet images from 0.1 to 1.0 arcsec

WFIRST will

measure galaxy shapes to map dark matter and measure the growth of galaxies over the Universe's life

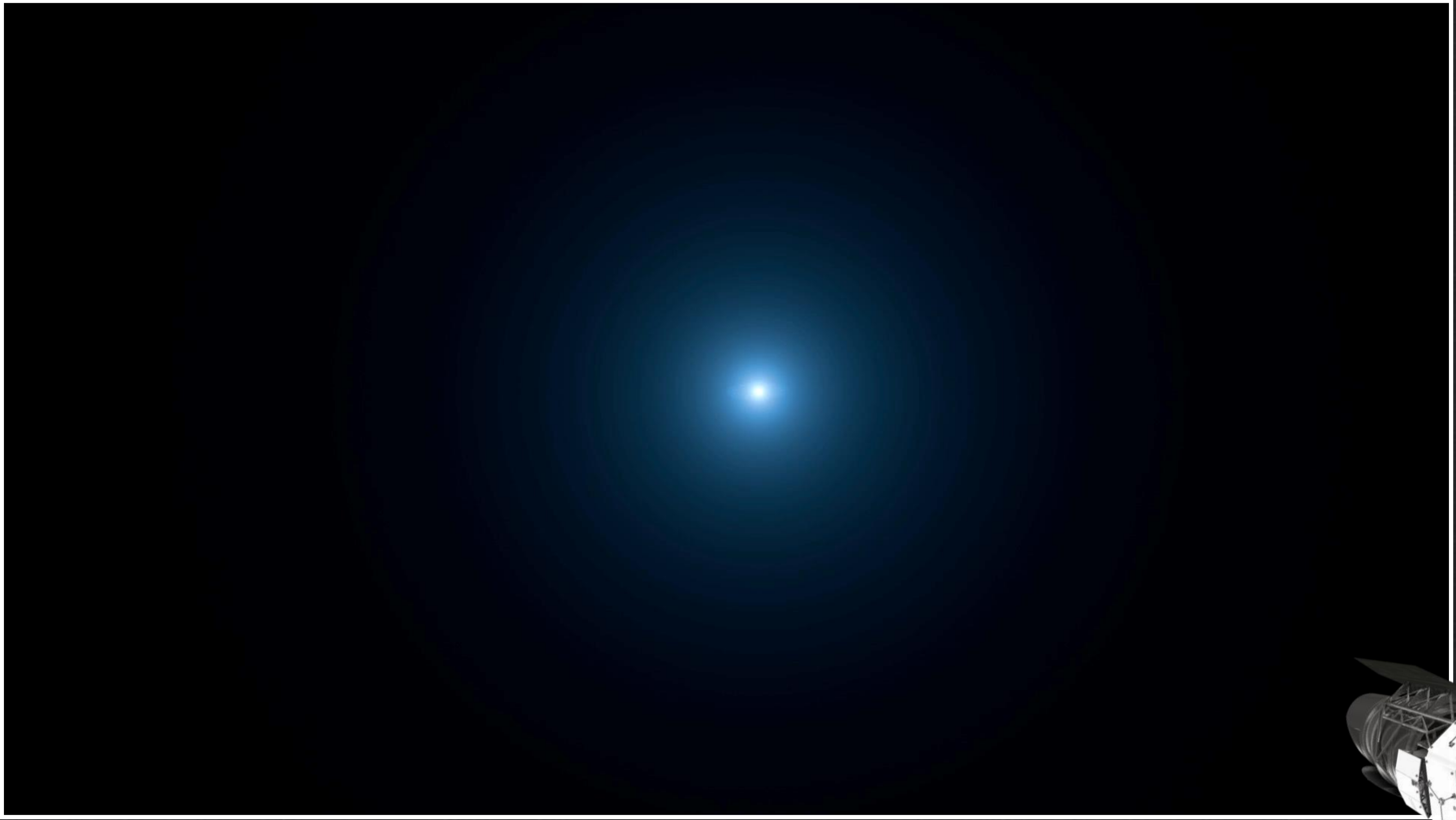


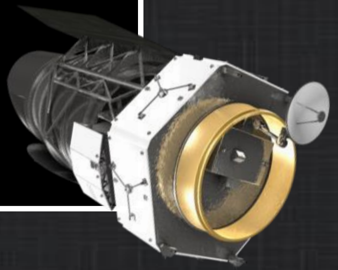


#NASAWFIRST

WFIRST will

map the positions of galaxies to establish a cosmic standard ruler to measure the Universe’s expansion history

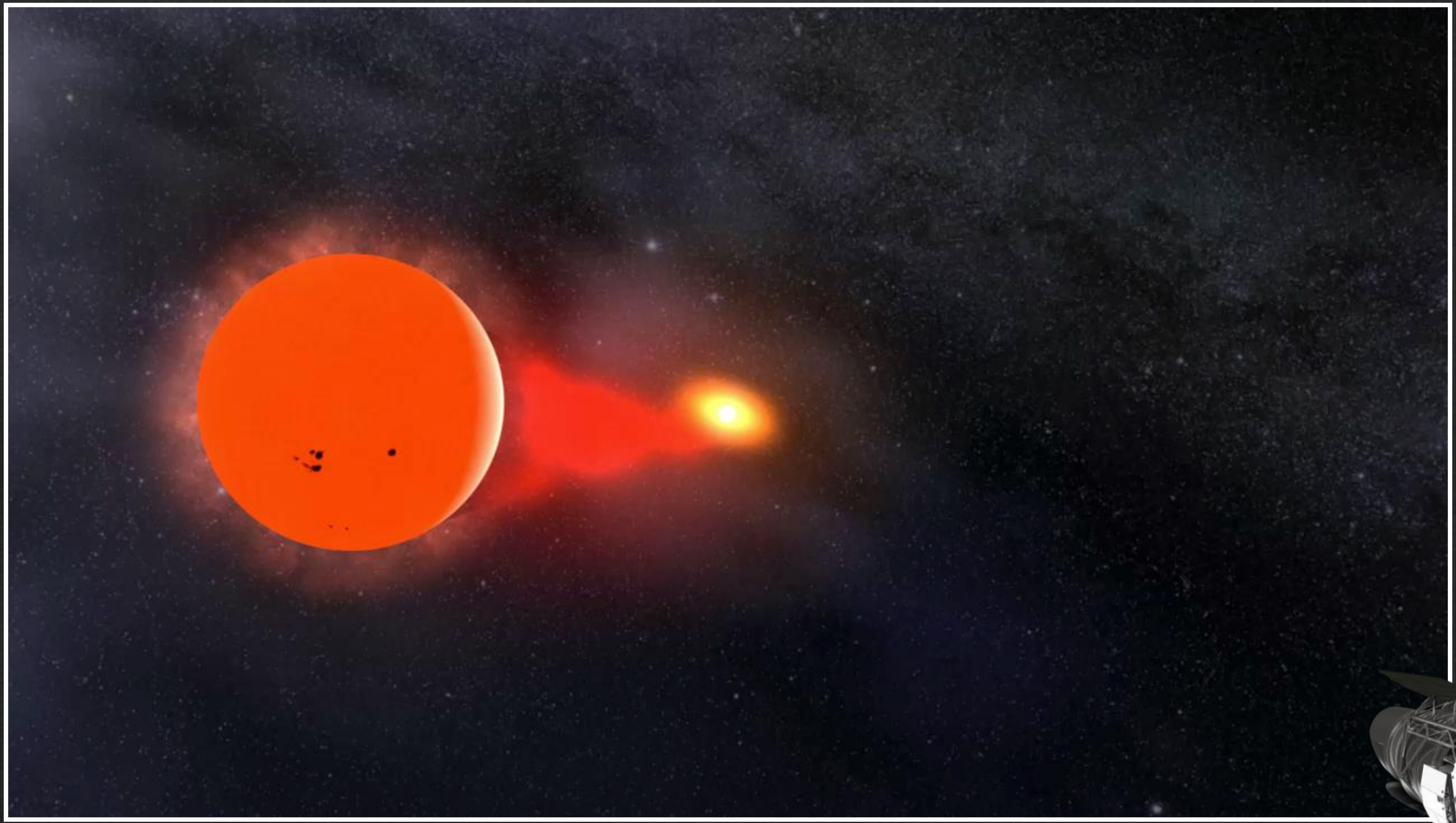


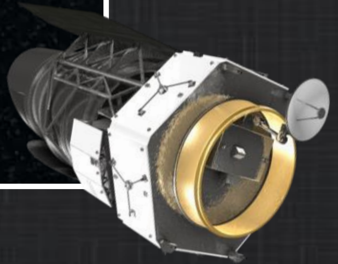


#NASAWFIRST

WFIRST will

discover exploding stars (supernovae) across cosmic time to establish precise distances to galaxies





#NASAWFIRST

Nominal Deep Fields

Table 2.

Field[a]	R.A.	Dec.	Ecl. Lat.	Area	E(B-V)	Zodi[b]	Days/Year	No. of Spectra[c]
				CVZ fields ($< 36°$)				
SEP	06:00	−66:33	−90	100	0.062	1.0	365	
GOODS-N	12:36	+62:13	+57	0.25	0.012	1.2	365	
Extended Groth Strip	14:17	+52:30	+60	0.2	0.009	1.2	365	
Elias N-1	16:11	+55:00	+73	9	0.008	1.0	365	
Elias N-2	16:46	+41:01	+63	5	0.014	1.1	365	
Deep2A	16:52	+34:55	+57	1	0.018	1.2	365	
IRAC Dark Field	17:40	+69:00	+87	0.2	0.043	1.0	365	
NEP	18:00	+66:33	+90	100	0.046	1.0	365	
Akari Deep Field South	04:44	−52:20	−73	12	0.008	1.0	365	
				Non-CVZ fields				
Elias S-1	00:35	−43:40	−43	7	0.008	1.5	215	
XMM-LSS	02:31	−04:30	−18	11	0.024	3.2	155	
CDFS	03:32	−27:48	−45	0.3	0.008	1.4	229	
Lockman Hole	10:45	+58:00	+45	11	0.011	1.4	229	
COSMOS	10:00	+02:12	−9	2	0.018	6	148	
VVDS14h	14:00	+05:00	+16	4	0.026	3.6	153	
Bootes	14:32	+34:16	+46	9	0.016	1.4	236	
SSA22	22:17	+00:24	+10	4	0.056	5.6	149	
Deep2B	23:30	+00:00	+3	1	0.044	19	146	
SPT Deep	23:30	−55:00	+46	100	0.010	1.4	236	
HERA	07:00	−30:43		1200				

[a]For populating the columns in this table, please see the full Excel spreadsheet at:
http://wfirst.wikispaces.com/file/view/Deep-Field-WG-2017-04-12-Peter-Capak-Euclid.xlsx